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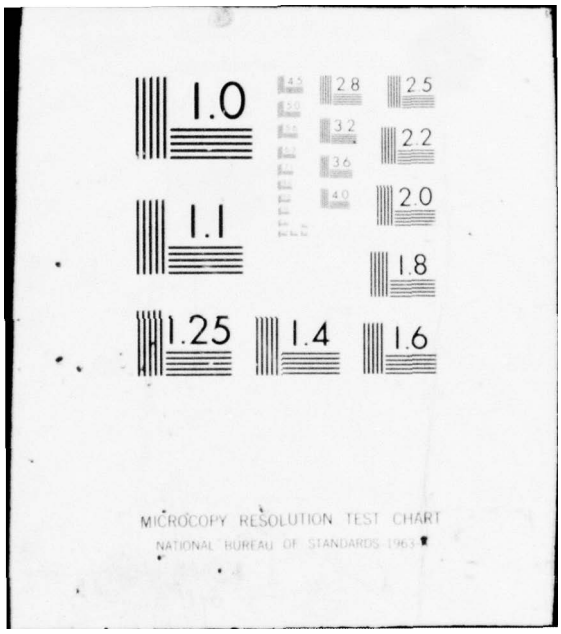
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MISCELLANEOUS PAPER Y-76-4

SENSITIVITY ANALYSIS OF THE WATER QUALITY FOR RIVER-RESERVOIR SYSTEMS MODEL

by

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER: Miscellaneous Paper Y-76-4
2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER: WES-MP-Y-76-4

4. TITLE (and Subtitle): SENSITIVITY ANALYSIS OF THE WATER QUALITY FOR RIVER-RESERVOIR SYSTEMS MODEL
5. TYPE OF REPORT & PERIOD COVERED: Final report
6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s): Kent W. Thornton, Allan S. Lessem
8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS: U. S. Army Engineer Waterways Experiment Station, Environmental Effects Laboratory, P. O. Box 631, Vicksburg, Miss. 39180
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS

11. CONTROLLING OFFICE NAME AND ADDRESS: Office, Chief of Engineers, U. S. Army, Washington, D. C. 20314
12. REPORT DATE: September 1976
13. NUMBER OF PAGES: 49 (53 p.)

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)
15. SECURITY CLASS. (of this report): Unclassified
15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Computerized simulation	Mathematical models
Data collection	Sensitivity
Ecosystems	Water quality

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Most total ecosystem models require extensive data sets for initializing and calibrating the model to the prototype system. Data collection programs, however, are expensive and time-consuming. To obviate these constraints, the data collection program should be guided by a knowledge of the model sensitivity to various initial conditions and coefficients. A software program was developed for the Honeywell 600 computer system that permitted an evaluation of sensitivity of coefficients and initial conditions in the WQRRS model. (Continued) Next p

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20. ABSTRACT (Continued)

The program permitted the display of 21 water quality variables on the same plot and a comparison of the responses produced by changing one coefficient by 10 percent. In general, the model results were more sensitive to 10-percent changes in coefficients at high nutrient concentrations than at low nutrient concentrations. The model results were quite sensitive to a 10-percent change in the evaporation and dispersion (effective diffusion) rate coefficients, biota growth, respiration, and temperature rate coefficients. The nutrient regime affected the sensitivity of the half-saturation coefficients and stoichiometric equivalences. Sensitivity analyses perform a useful function in modeling programs. First, sensitivity analyses provide insight into the interrelation of various compartments and the overall functioning of the system. Second, a more effective and inclusive data-collection program can be designed when the results of sensitivity analyses are combined with the project objectives and constraints. Finally, sensitivity analyses may be expediently conducted at small cost on an initial data set for the prototype system.

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Preface

The passage of the 1969 National Environmental Policy Act (NEPA) required that Federal agencies address the environmental impact of all proposed projects. Subsequent interpretations of NEPA required that Federal activities such as a major change in the operating guidelines of an impoundment must also address the environmental impact of the activity. One approach toward the prediction of environmental impact is the use of mathematical simulation models. This report was prepared as initial guidance for the District offices on the sensitivity of an available ecological model for reservoirs and to emphasize the importance of sensitivity analysis in simulation studies.

This is one of several reports being prepared by the Environmental Effects Laboratory (EEL) at the U. S. Army Engineer Waterways Experiment Station (WES) as part of a comprehensive work unit on the Evaluation and Application of Mathematical Reservoir Ecosystem Models. The purpose of the work unit is to analyze, refine, improve, and verify existing mathematical models as useful management tools. During this evaluation, the models will be improved and refined to reflect greater biological and chemical realism and these improved models will be made available for field use in District project studies. Evaluating the sensitivity of models under different environmental regimes such as a shallow, warm-water reservoir versus a deep, cold-water power project is one approach toward assessing the model's general applicability and realism for prediction.

No mathematical model will predict absolute values. For some variables, the predicted values may not be within an order of magnitude of observed field data. However, if the models are calibrated properly and the output interpreted with a knowledge and understanding of the model assumptions and limitations, trends may be predicted that provide valuable information about the nature and relative magnitude of impacts on a proposed activity. Data sets are being collected on various projects throughout the Corps to verify the predictive capability and the transferability of these mathematical models.

The research reported here was funded through the Civil Works Environmental Impact Research Program, Office, Chief of Engineers (OCE). Mr. John Bushman was the Technical Monitor. This report was prepared by Drs. K. W. Thornton and A. S. Lessem under the direction of Mr. D. L. Robey, Ecosystem Modeling Branch, and the general direction of Drs. R. L. Eley and J. Harrison, EEL, WES. Guidance on the initial selection of model coefficients and additional information on the approach to sensitivity analyses can be obtained by contacting Dr. K. W. Thornton (FTS 542-3713) or Dr. A. S. Lessem (FTS 542-3623), WESYS, Vicksburg, Miss. 39180.

The Directors of the WES during the course of this study and the preparation and publication of this report were COL G. H. Hilt, CE, and COL J. L. Cannon, CE. Technical Director was Mr. F. R. Brown.

CONTENTS

	Page
Preface	2
Summary	5
Introduction	6
The Model	7
Approach to Sensitivity Analysis	8
Model Sensitivity	10
Model Application	12
Literature Cited	14
Tables 1-3	
Figures 1-30	

Summary

This report presents initial results of a sensitivity analysis conducted on the Water Quality for River-Reservoir Systems (WQRRS) model.

A computer program was developed for the Honeywell 600 system that permitted the display of 21 water quality variables in the WQRRS model and their sensitivity to a 10-percent change in some of the model coefficients. The sensitivities were examined under high and low nutrient regimes. The model response, in general, was more sensitive under the high nutrient regime. The model was most sensitive to a 10-percent change in the evaporation and dispersion rate coefficients, biota growth and respiration rate coefficients, and temperature coefficients. The nutrient regime affected the sensitivity of the half-saturation coefficients and stoichiometric equivalences.

This report demonstrates the utility of sensitivity analysis and indicates it should be an integral part of any modeling program. Sensitivity analyses are useful for identifying model input and coefficients whose variation may cause significant changes in model output. Based on the results of sensitivity analyses, emphasis can be placed on sensitive parameters during field data collection and in selecting rate coefficient values. Since many factors such as temperature and nutrient regimes may significantly influence the model sensitivity, a comprehensive sensitivity analysis may be necessary before a general understanding of the model output is achieved.

SENSITIVITY ANALYSIS OF THE WATER QUALITY FOR RIVER-RESERVOIR SYSTEMS MODEL

Introduction

Total ecosystem models have become diagnostic tools for many water-quality studies. These studies include the analysis of possible environmental consequences resulting from changes in the operation of existing impoundments or from alternative designs and management strategies in proposed impoundments. Most total ecosystem models such as CLEAN,[1] HYDRO-SCI,[2] or WQRRS[3] require extensive data sets for initializing and calibrating the model to the prototype system. In most studies on existing impoundments and on all pre-impoundments, the data set is generally sparse. Data collection programs are expensive and time-consuming, so it is important that pertinent and accurate data be collected for any modeling effort. In part, the data collection should be guided by a knowledge of the model sensitivity to various initial conditions and coefficients. The greatest effort can then be directed toward characterizing those coefficients that result in the greatest model sensitivity and minimize the effort on insensitive parameters.

This paper will describe an initial sensitivity analysis conducted on the Water Quality for River-Reservoir Systems (WQRRS) model by the Environmental Effects Laboratory at the U. S. Army Engineer Waterways Experiment Station. These results represent initial findings and are a part of a comprehensive effort to evaluate the sensitivity and transferability of the WQRRS model to different data sets and to assess the realism of the model in predicting ecosystem responses.

The Model

The WQRRS model was originally developed by Water Resources Engineers (WRE) under a Title II contract from the Office of Water Resources Research[4] and was subsequently modified for the Corps of Engineers.[3] The model is conceptually based on the division of an impoundment into discrete horizontal layers. The model assumptions are:

a. An impoundment can be represented by a series of one-dimensional horizontal slices. This implies that only the vertical dimension is retained during computation. This assumption is generally satisfactory for impoundments with long residence times.[3]

b. Isotherms are parallel to the water surface both laterally and longitudinally.

c. Each horizontal layer is assumed to be completely homogeneous and instantaneously mixed for all components.

d. Internal advection and heat transfer occur only in the vertical direction.

e. External advection (inflow and outflow) occurs as a uniform horizontal distribution within each layer.

f. Internal dispersion of thermal energy occurs by a diffusion mechanism that combines the effects of molecular diffusion, turbulent diffusion, and thermal convection.

g. The dynamics of each chemical and biological component can be expressed by the Law of Conservation of Mass and the Kinetic Principle.[4]

The computer approximates the numerical solution of the mass-balance differential equations in finite difference form using an implicit solution

technique. The tabular output from the model includes information on meteorological conditions, inflow-outflow quality and quantity, predicted fishery standing crops, and a vertical profile of predicted in-lake water-quality constituents. The model is programmed in FORTRAN and has been run on IBM, CDC, UNIVAC, and Honeywell systems. Considering the hydrodynamics, biology, chemistry, and data requirements, the WQRRS model is presently one of the most comprehensive and reservoir ecosystem models available for practical applications.

Approach to Sensitivity Analysis

Sensitivity is a function of many factors including the particular data set, the dynamics of the system, the initial conditions, and time. In order to study these factors in a comprehensive way, a software program was developed for the Honeywell 600 system that permitted making an initial base run; storing all the generated daily values for each of the 21 water quality constituents at two depths in the reservoir, 1 m below the surface and 2 m above the bottom; changing only one coefficient by 10 percent; rerunning the entire simulation; and making a daily comparison between the base values and the counterpart responses after perturbation. If there were no difference before and after the perturbation, the ratio of the two responses for each constituent would be unity. If there was an increase in the constituent value after perturbation, the ratio would be greater than one; correspondingly, a decrease in the constituent value would produce a ratio less than one.

The response values were displayed graphically by a CRT plotter. A generalized sensitivity plot is shown in Figure 1. By using polar coordinates where each angular degree represents one Julian day, all 21 constituents can be displayed on the same plot. If no response occurs, a unit circle results. A vector drawn from the origin out to the value for the perturbed response can be used to measure the magnitude of individual values. With reference to Figure 1, the unit circle is, by definition, one unit from the origin and the end of the x,y axis is two units from the origin, representing a response twice as great as the base response. In some instances, the response was greater than three times the base value. These values will not appear on the plot since the CRT plotter was instructed to ignore values this large or larger to prevent overlapping plots. This results in a discontinuity in the plot from the point where the values exceed a ratio of 3.0 to the point where the values are less than a ratio of 3.0.

Several variables (e.g., dissolved oxygen (DO), zooplankton, and coliforms) exhibit anomalous spikes in the plots, primarily in the bottom depth. This data set resulted in low hypolimnetic values for these variables. In most instances, these spikes are numerical artifacts arising from the division by small numbers. For example, if a 10-percent change in a coefficient resulted in a one-day lag from the base value in the reduction of the coliform concentration from 1.0 to 0.25 MPN/100 ml, the ratio would be 1.0 (perturbed value)/0.25 (base value) or 4.0 and a spike would result. Since the hypolimnion did become anoxic during the simulation, a similar ratio might occur for DO.

These spikes did not occur in the epilimnion for DO. Zooplankton are typically found in low numbers so a lag resulting in a decrease from 4.0 to 2.0 µg/ℓ would result in a ratio of 2.0, also appearing as a spike. The next iteration might again predict a ratio of unity or 1.0.

Sensitivity analyses were conducted by increasing one coefficient by 10 percent and observing the resulting changes in other system variables. Variables that changed by 10 percent or less were considered insensitive to the coefficient. All variables that changed more than 10 percent were considered sensitive.

The abbreviated names shown on the figures and used later in the text are defined in Table 1.

Model Sensitivity

The sensitivity analysis was conducted only on the reservoir portion of the WQRRS model. The data set was compiled for a pre-impoundment study conducted by the WES. The first plot in each series is representative of the sensitivity of the model to high nutrient conditions. The nutrient conditions were reduced during the second series of runs to examine the sensitivity under a low nutrient regime.

Attention was given to various coefficients affecting the algae and fish compartments since these variables are of interest in many projects. The sensitive variables are listed in Table 2.

The sensitivities generated during parameter variation were strongly influenced by the nutrient regime. In general, the model results were more sensitive to 10-percent changes in coefficients at higher nutrient

concentrations. Some coefficient sensitivities were inversely related to nutrient concentrations (i.e., sensitive at low concentrations and insensitive at high concentrations or vice versa). This was true primarily for the biological and chemical coefficients.

The model response was very sensitive to changes in evaporation and diffusion (dispersion) rate coefficients, but the sensitivity of the physical coefficients was lower at the lower nutrient concentrations (Figures 2-5). The maximum sensitivity for ALGAE 1 under the high nutrient regime, for example, was 237 percent for evaporation, 115 percent and 456 percent for the A1 and A3 dispersion coefficients, respectively.

The biological compartments, in general, were sensitive to changes in the growth and respiration rate coefficients. A 10-percent change in the ALGAE 1 growth rate resulted in a 41-percent increase in ALGAE 1 standing crop and a 58-percent decrease in the ALGAE 2 standing crop. A 10-percent change in the ALGAE 2 growth rate under the high nutrient regime resulted in a 267-percent increase in ALGAE 2 with no significant change in ALGAE 1 (Figure 6). A 10-percent change in the ALGAE growth rates under the low nutrient regime elicited much less response (Figure 7). The model response was also sensitive to changes in the algae settling rate and self-shading coefficients; the fish half-saturation coefficients; ammonia, detritus, and coliform decay rates; and to the coliform Q-10 factor regardless of the nutrient concentration. It also appears important to establish the correct range for the minimum to optimum

temperatures. Fortunately, this information is generally available for most species (Figures 8-28).

Nutrient concentrations affected the sensitivity of the model to the algae half-saturation constants and the stoichiometric equivalences. The ALGAE 1 compartment was sensitive to a change in the phosphorus half-saturation constant at low nutrient concentrations and insensitive at high nutrient concentrations (Figure 9). However, the CO2 and light half-saturation concentrations affected the ALGAE 1 response at high but not low nutrient concentrations (Figure 10). Similarly, the model response was sensitive to changes in the O2-NH3, O2-NO2, and O2-RESP stoichiometric equivalences at high nutrient levels (Figures 29-30). The model was also sensitive to the algae carbon fraction at high concentrations and sensitive to the detritus phosphorus fractions at low concentrations (Figures 8 and 18, respectively).

The effect of changing initial conditions was studied by perturbing the initial reservoir temperature, dissolved oxygen, nitrate, phosphate, and algae profiles. This 10-percent increase decayed fairly rapidly and did not significantly influence the other compartments. This increase, however, occurred on 1 January under isothermal and isotropic conditions. It is not known if similar results would have occurred if conditions would have been perturbed later in the year.

A table of insensitive coefficients for this particular application is also included (Table 3).

Model Application

While these results represent only an initial effort in a

comprehensive study, the findings indicate sensitivity analyses should be considered as an integral part of a modeling program. First, sensitivity analyses provide insight into the interrelation of various compartments and the overall functioning of the system. This insight is invaluable during the interpretation and conclusion phase of model applications. Second, a more effective and inclusive data-collection program can be designed when the results of sensitivity analyses are combined with the project objectives and constraints. Finally, sensitivity analyses may be expediently conducted at small cost on an initial data set for the prototype system. The exact sensitivities presented in this report are specific for a particular prototype system and will vary to some degree with other data sets, but the results do convey attributes of the general sensitivity of the WQRRS model.

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Table 1: Definition of Mnemonic Names

Mnemonic Name	Definition
TEMP	Temperature
DO	Dissolved Oxygen
ZO	Zooplankton
ALG1	Nannophytoplankton
ALG2	Net phytoplankton
DETR	Detritus
NH3N	Ammonia Nitrogen
NO3N	Nitrate Nitrogen
NO2N	Nitrite Nitrogen
PO4P	Orthophosphate Phosphorus
ALKA	Alkalinity as $CaCO_3$
COLF	Coliforms
TDS	Total Dissolved Solids
CARB	Total Carbon
SEDM	Sediment
BEN	Benthos
pH	--
CO2	Carbon Dioxide
DOD	Daily Oxygen Demand
FISH2	Warm Water Zooplankton Feeder
FISH3	Benthos Feeder

Table 2: Sensitive Variables*

Variable	Nutrient Regime
Atmospheric Turbidity Factor	High, Low
Evaporation Coefficient	High, Low
Diffusion Coefficient, A1	High, Low
Diffusion Coefficient, A3	High, Low
Algae 1 Growth Rate	High, Low
Algae 2 Growth Rate	High, Low
Algae 1 Settling Rate	High, Low
Algae Carbon Fraction	High
Algae 1 CO2 Half-Saturation Constant	High
Algae 1 PO4 Half-Saturation Constant	Low
Algae 1 Light Half-Saturation Constant	High
Self-Shading Coefficients	High, Low
Algae Respiration	High, Low
Algae 1 Temperature Coefficient T1	High
Algae 1 Temperature Coefficient T2	High, Low
Zooplankton Maximum Growth Rate	High, Low
Zooplankton Digestive Efficiency	High
Benthos Maximum Growth Rate	High, Low
Benthos Respiration	High, Low
Benthos Temperature Coefficient T2	Low
P Fraction, Detritus	Low
Fish 2 Maximum Growth Rate	High, Low

(Continued)

* Greater than 10-percent variation.

Table 2 (Continued)

Variable	Nutrient Regime
Fish 3 Maximum Growth Rate	High, Low
Fish 2 Zooplankton Grazing Half-Saturation Coefficient	High, Low
Fish 3 Benthos Grazing Half-Saturation Coefficient	High, Low
Fish Respiration	High, Low
Fish 2 Temperature Coefficient T2	High, Low
Fish 3 Temperature Coefficient T2	High, Low
Ammonia Decay Rate	High, Low
Coliform Decay Rate	High, Low
Coliform Q-10 Factor	High, Low
O2-NH3 Stoichiometry	High
O2-NO2 Stoichiometry	High
O2-Respiration Stoichiometry	High

Table 3: Insensitive Variables*

Variable	Nutrient Regime
Effective Length	High, Low
Effective Width	High, Low
Critical Stability	High, Low
Secchi Disc Depth	High, Low
Minimum Stability	High, Low
Algae 1 P HSC	High
Algae 1 N HSC	High, Low
Algae 1 CO2 HSC	Low
Algae 1 Light HSC	Low
Algae Carbon Fraction	Low
Algae Temp. Coef. T1	Low
Zo Digestive Eff.	Low
Zo Pref. for Algae 2	High, Low
Ben. Sed. Graze HSC	High, Low
Ben. Temp. Coef. T2	High
P Fraction Detritus	High
Fish 2 Temp. Coef. T3	High, Low
Detritus Decay Rate	High, Low
O2-NH3 Stoichiometry	Low
O2-NO2 Stoichiometry	Low
O2-RESP Stoichiometry	Low

(Continued)

* Less than 10-percent variation.

Table 3 (Continued)

Variable	Nutrient Regime
O2-DET Stoichiometry	High, Low
Initial Temp.	High, Low
Initial Dissolved Oxygen	High, Low
Initial NO3-N	Low
Initial Algae 1	Low
Initial Algae 2	Low

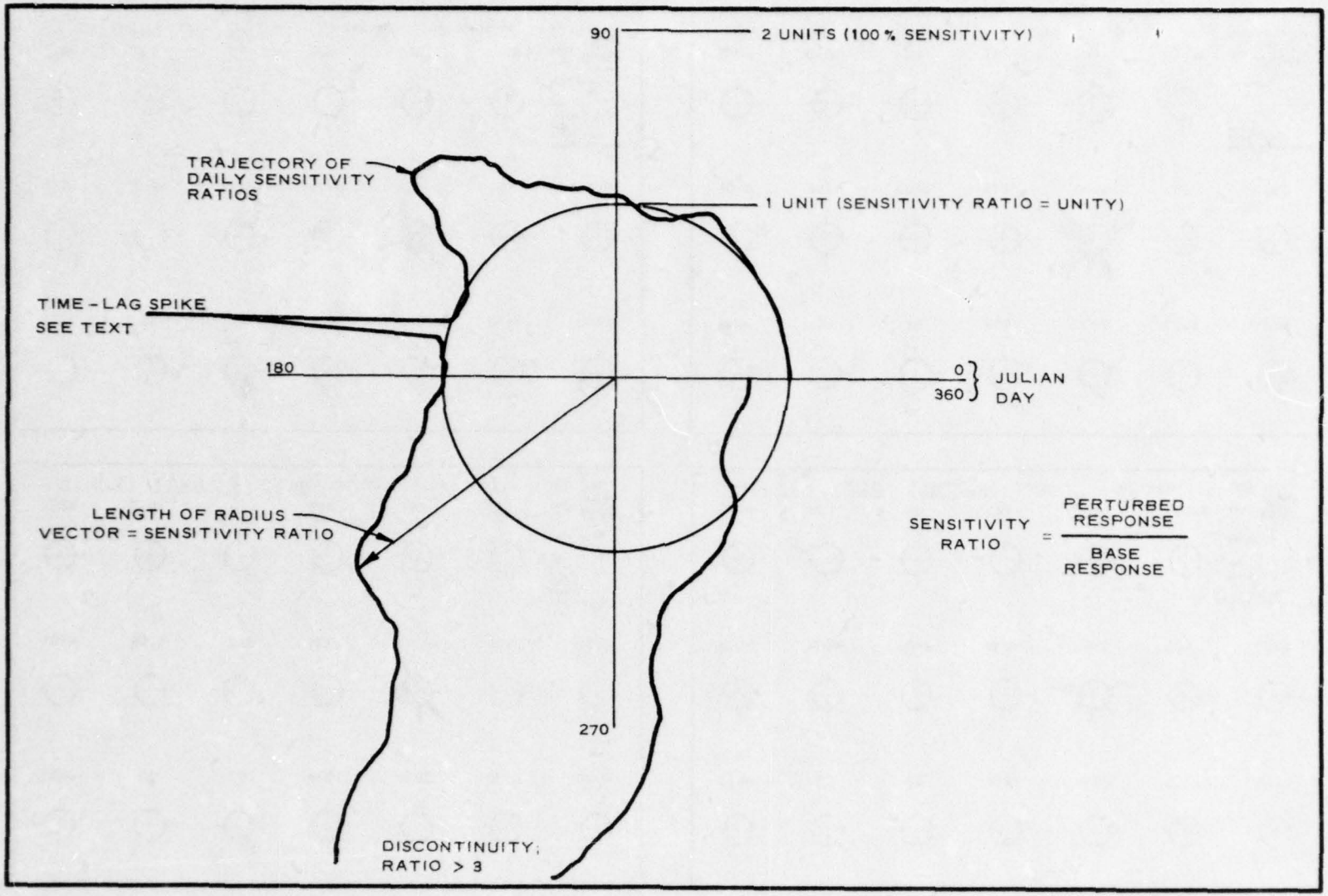


Figure 1. Generalized sensitivity plot

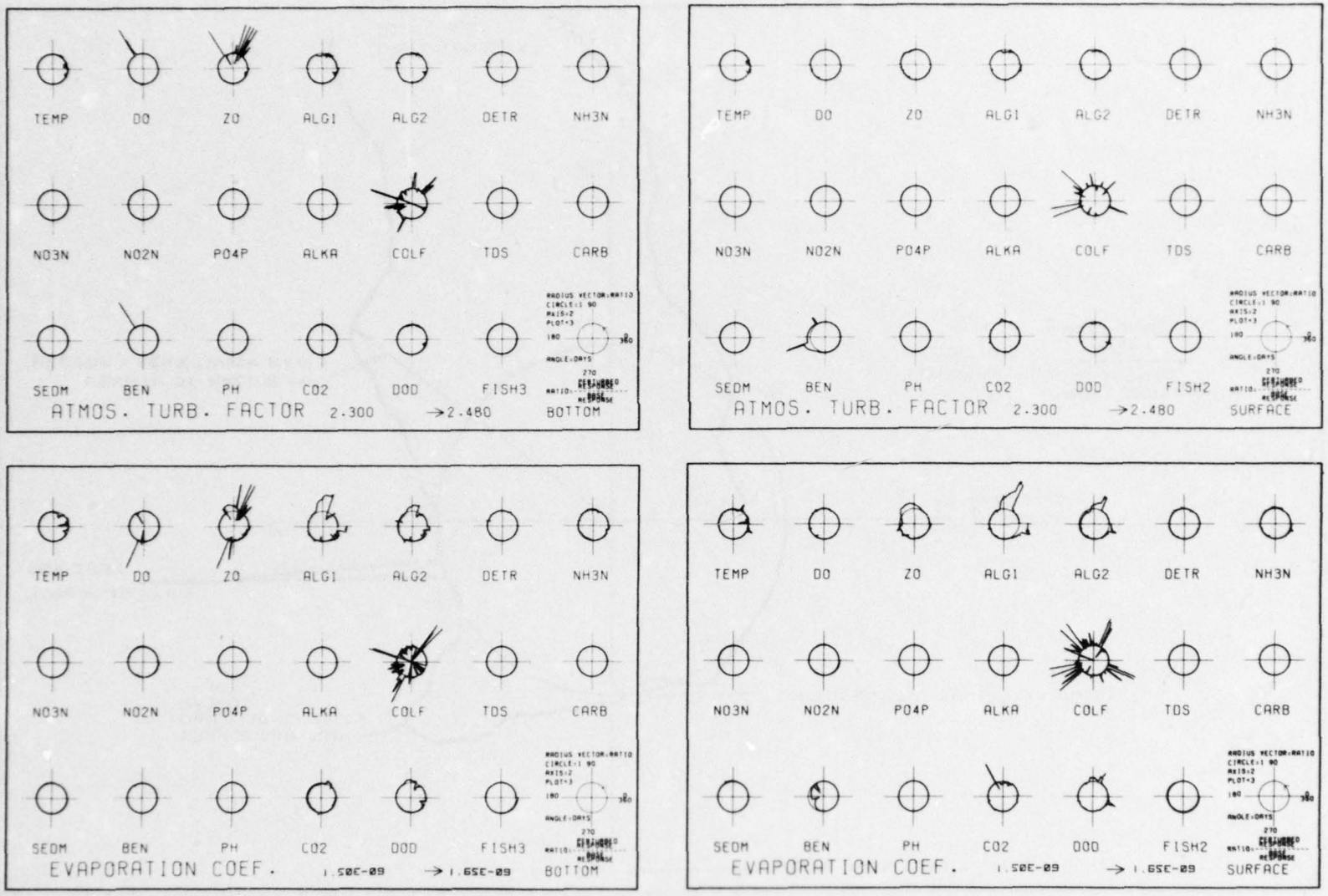


Figure 2. High nutrient case

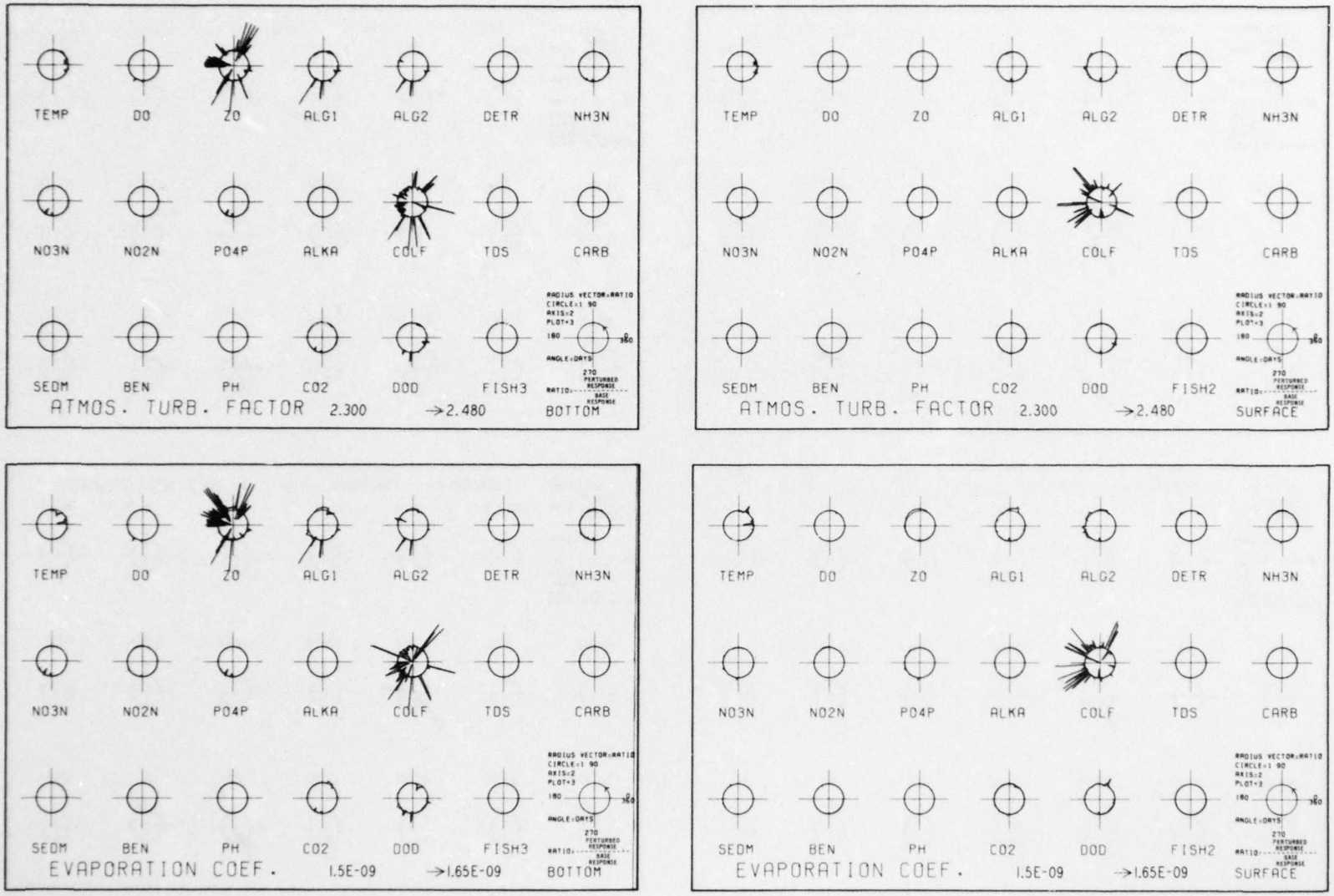
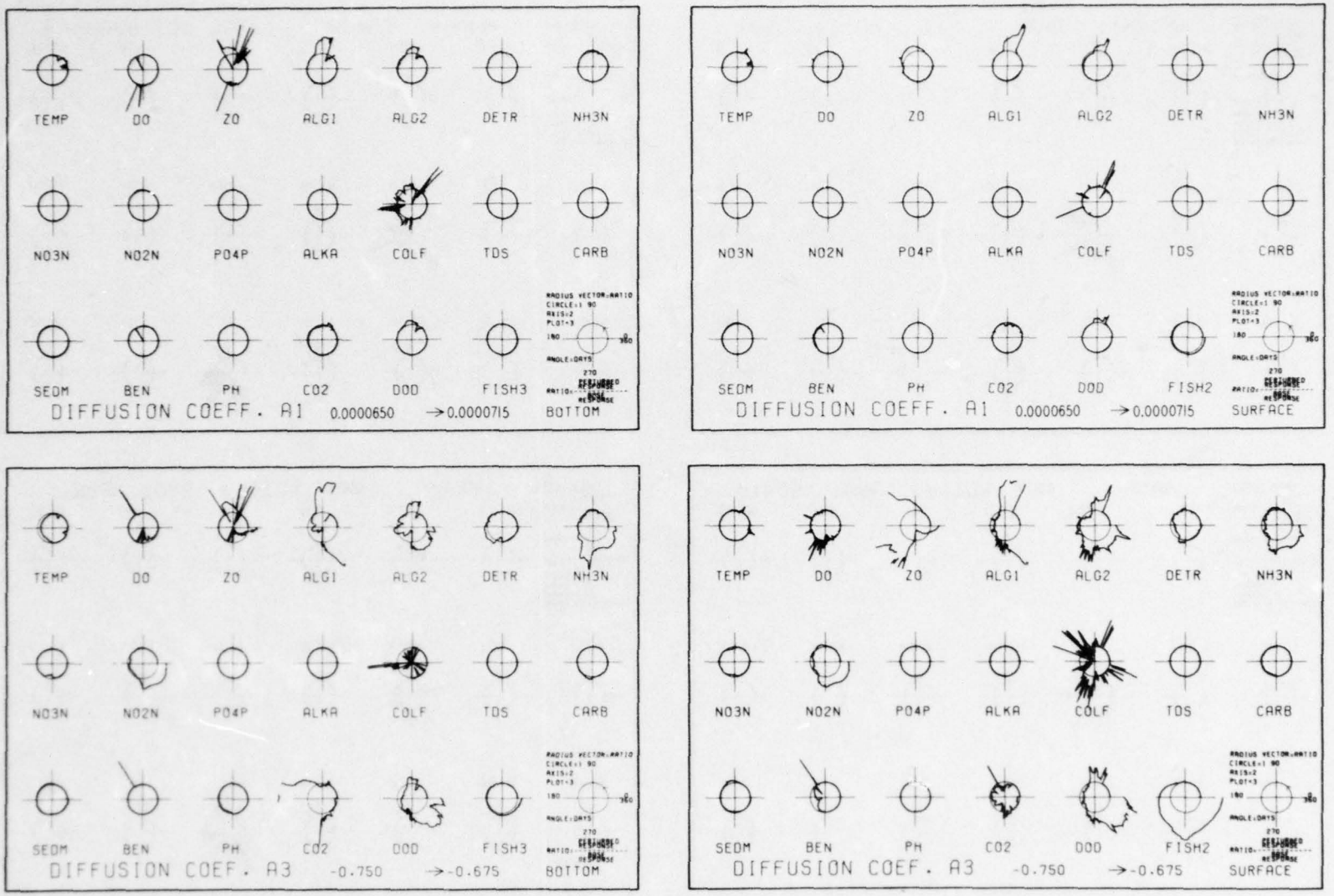


Figure 3. Low nutrient case



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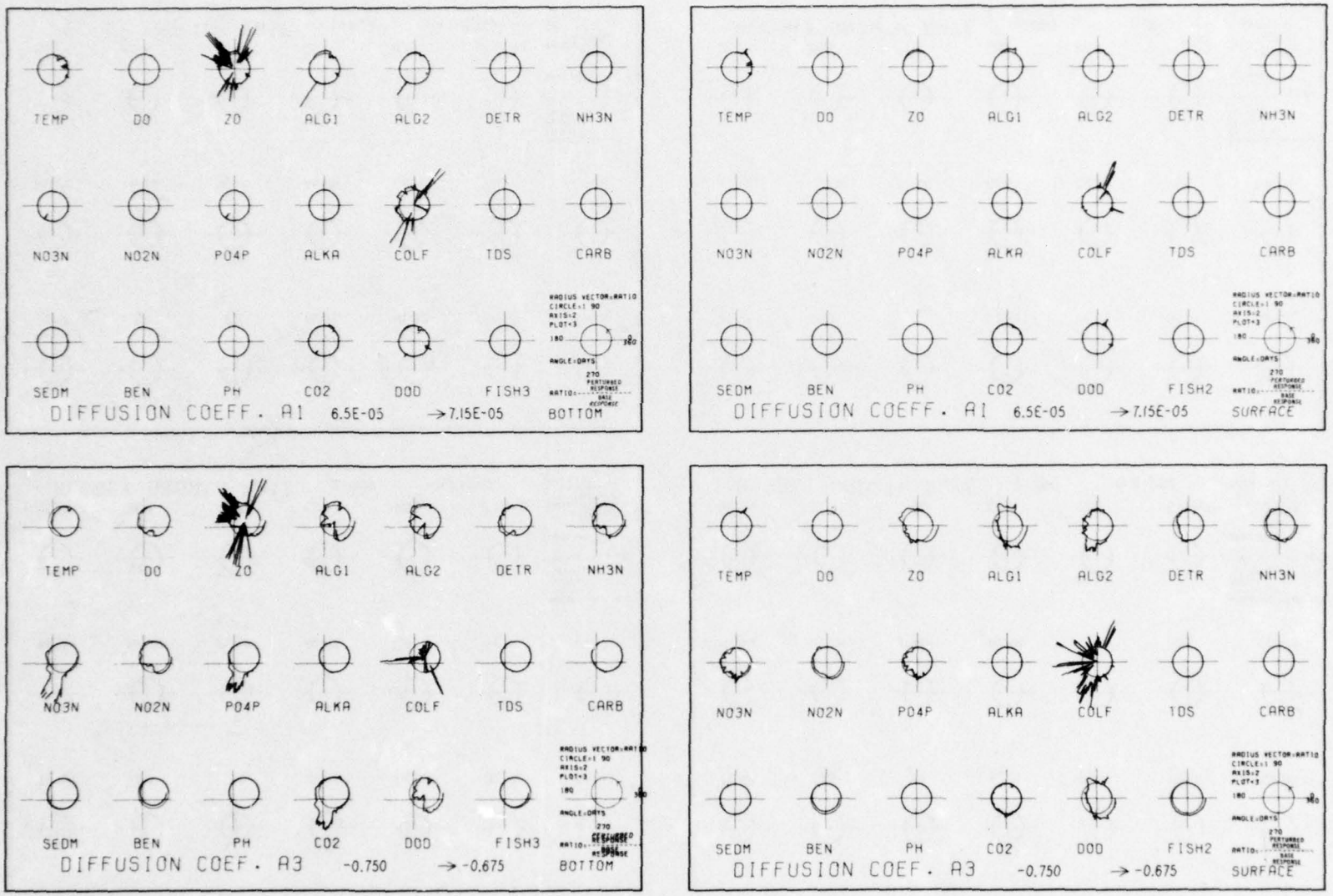

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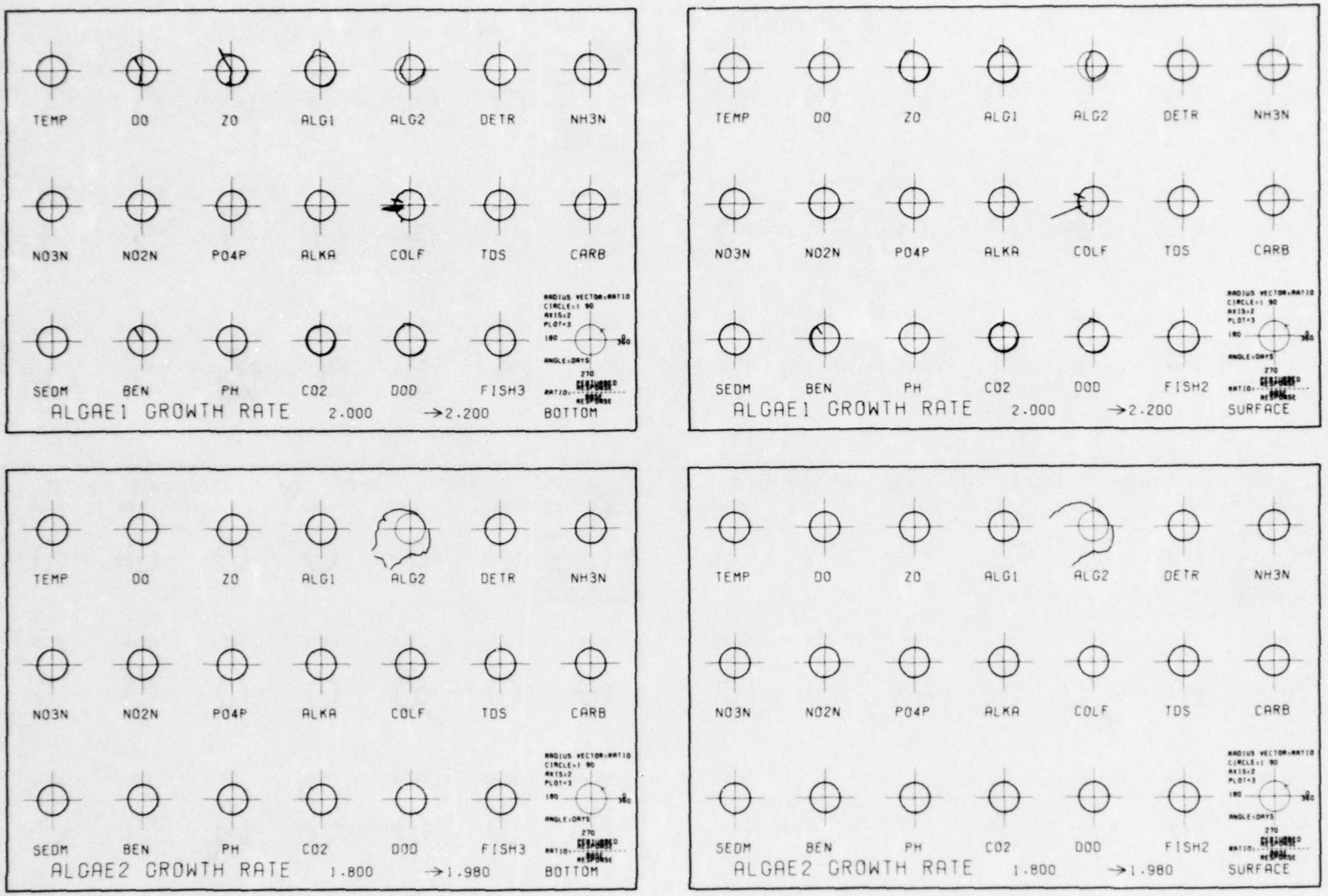

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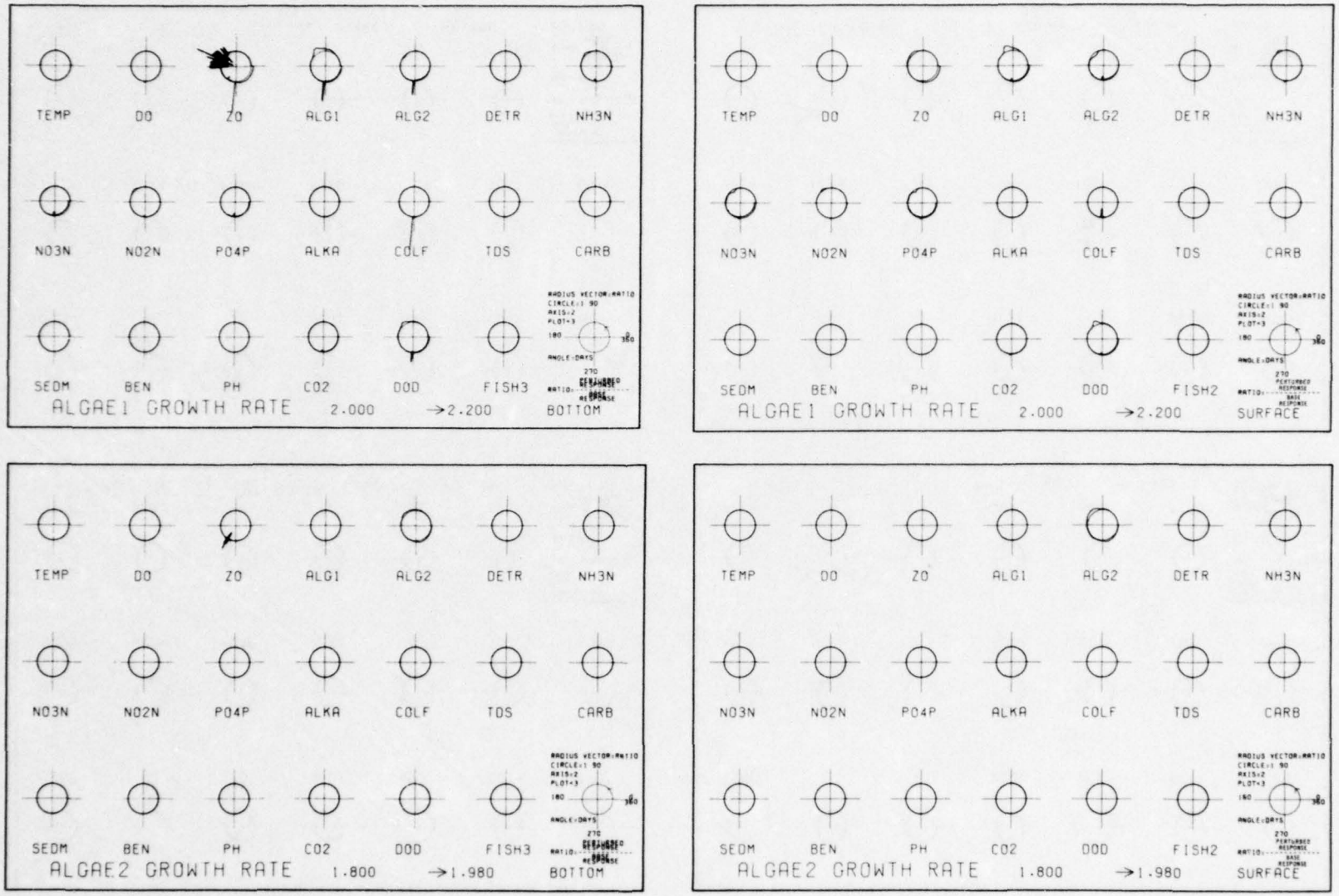

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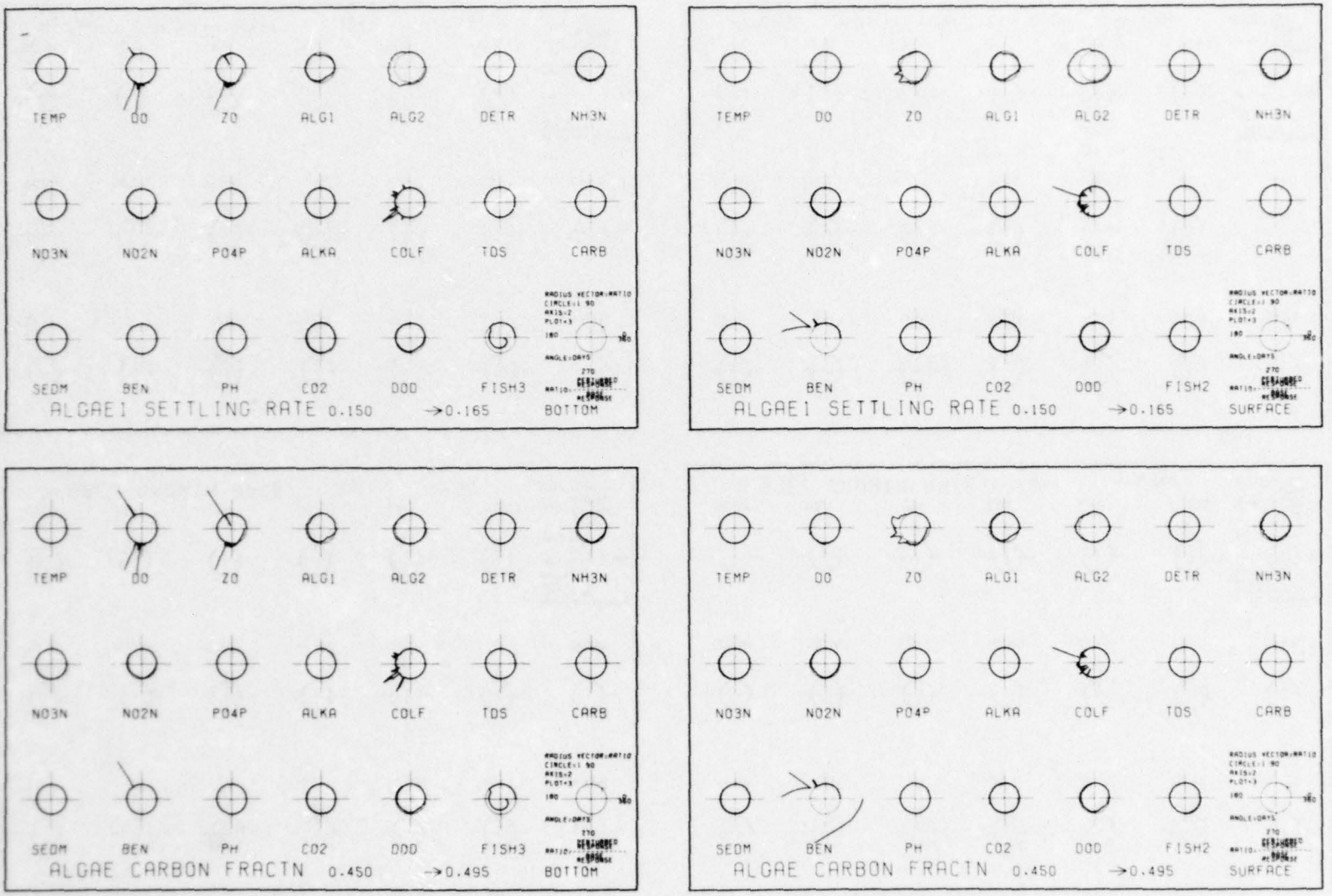


Figure 8. High nutrient case

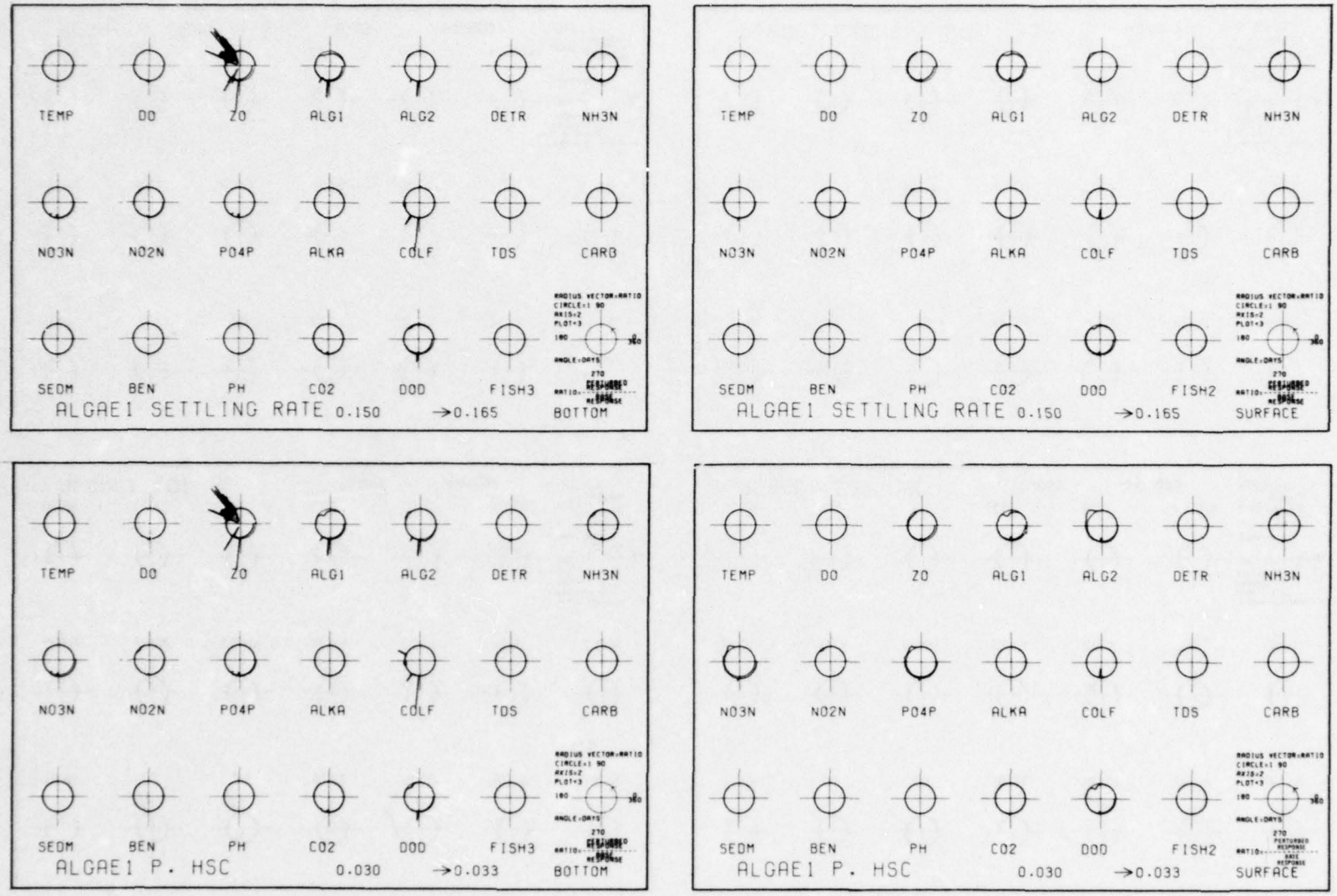
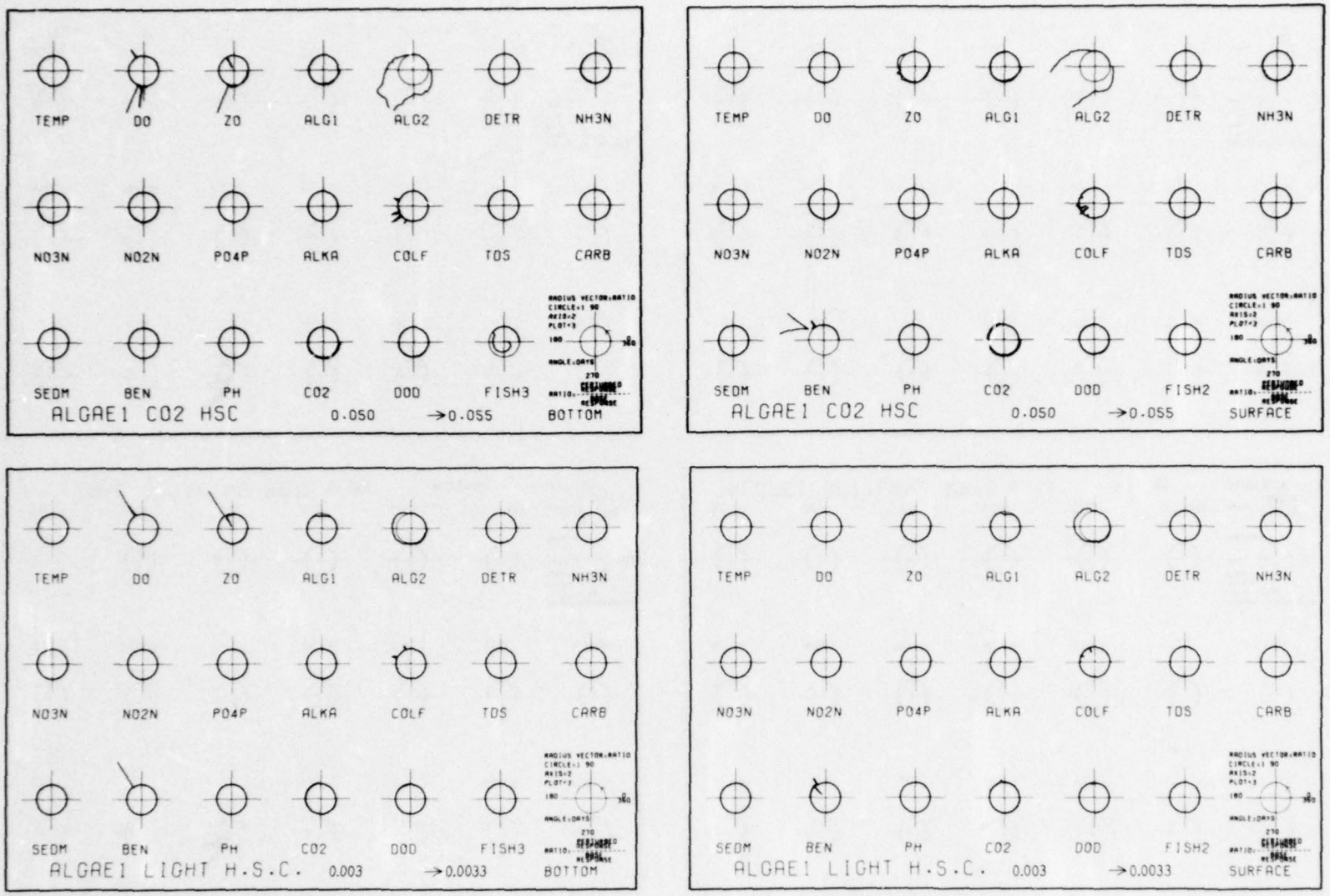


Figure 9. Low nutrient case



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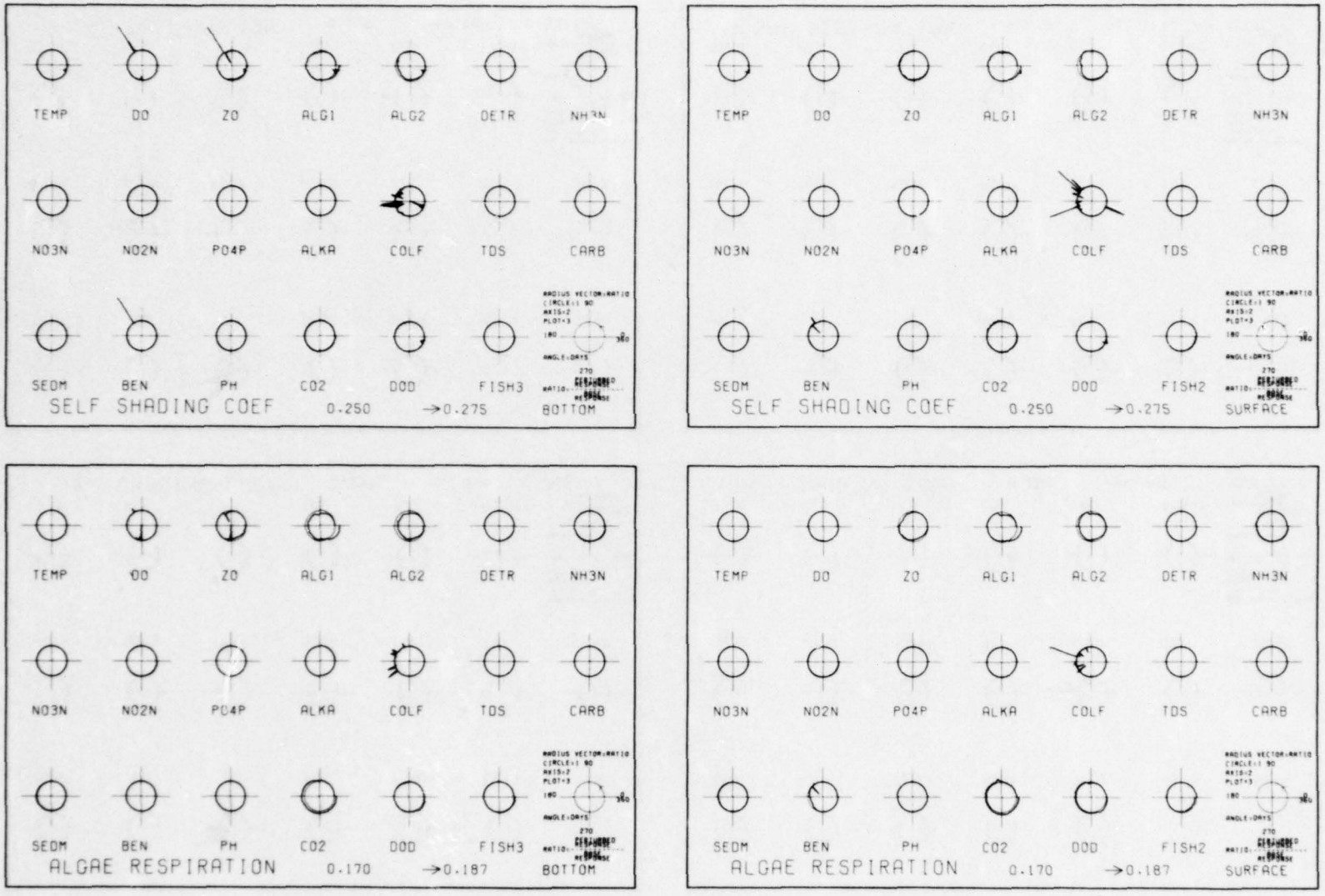

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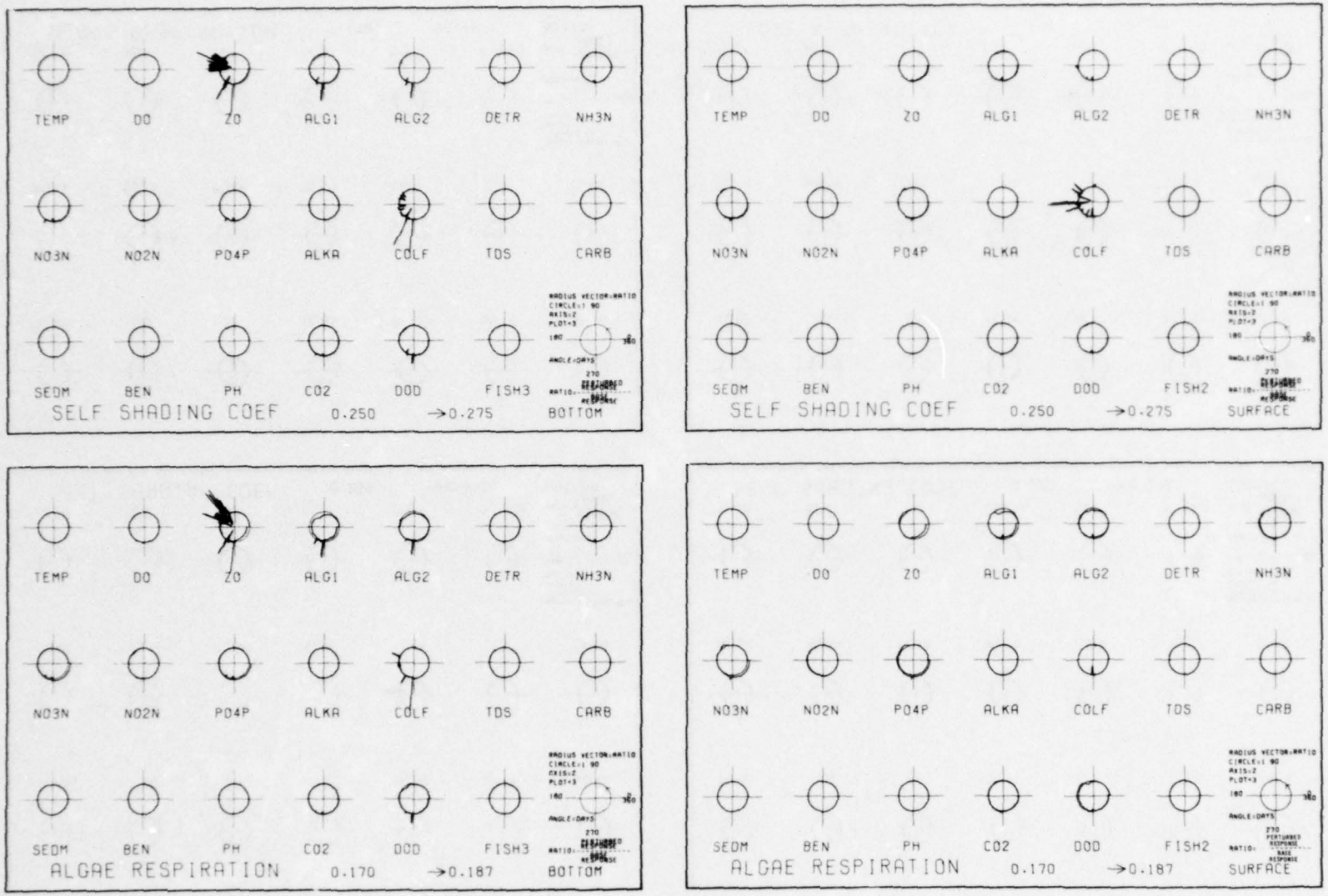

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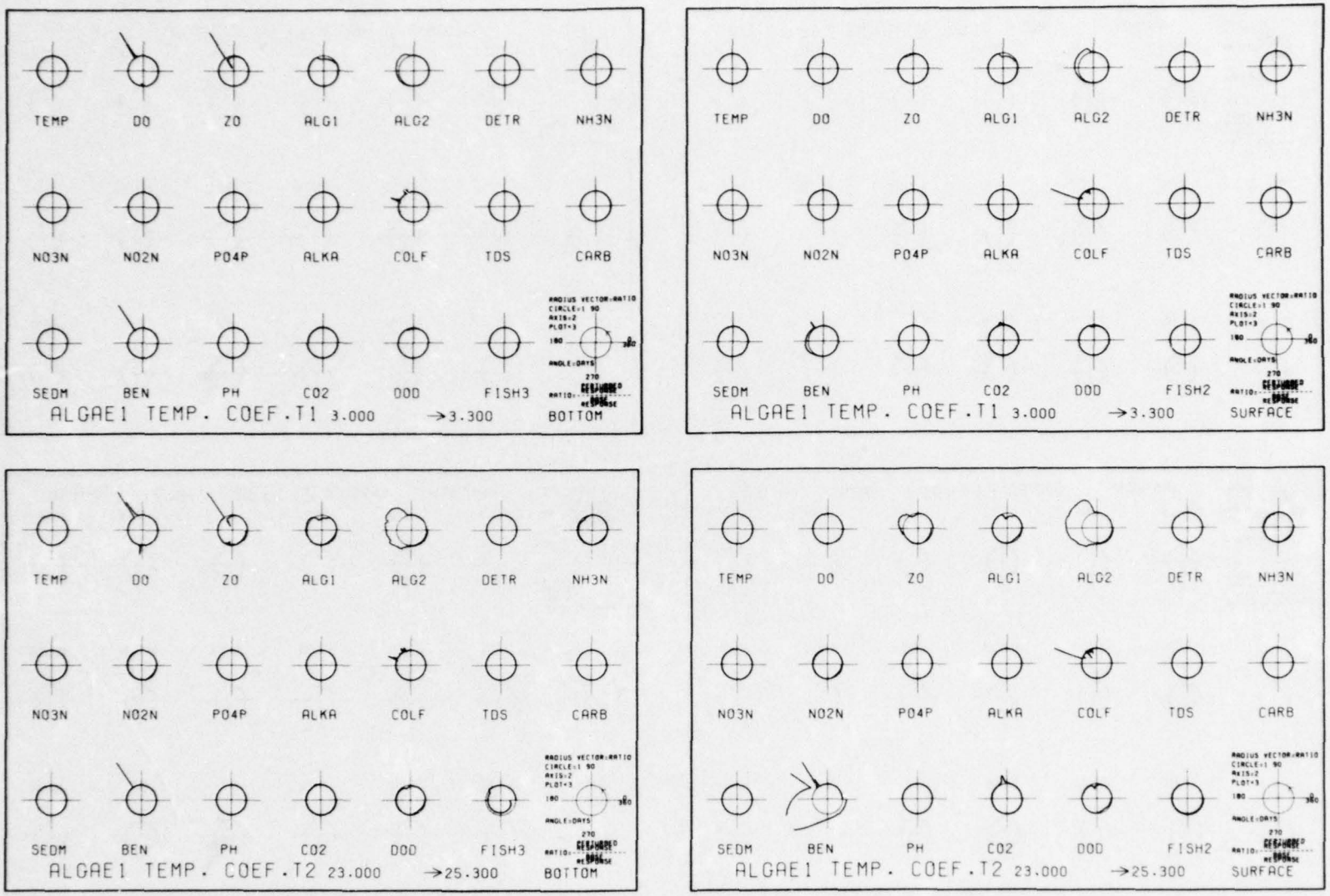


Figure 13. High nutrient case

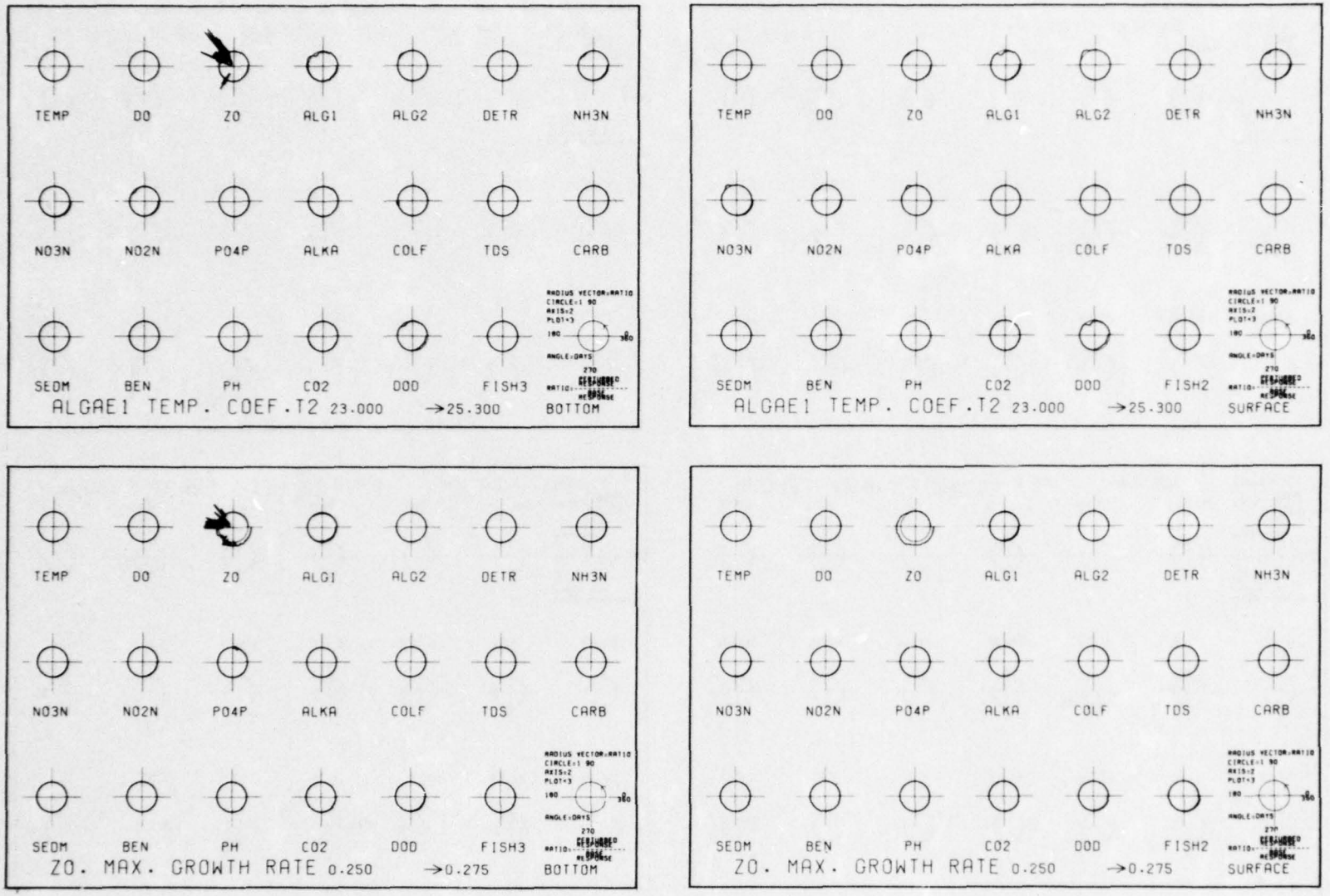


Figure 14. Low nutrient case

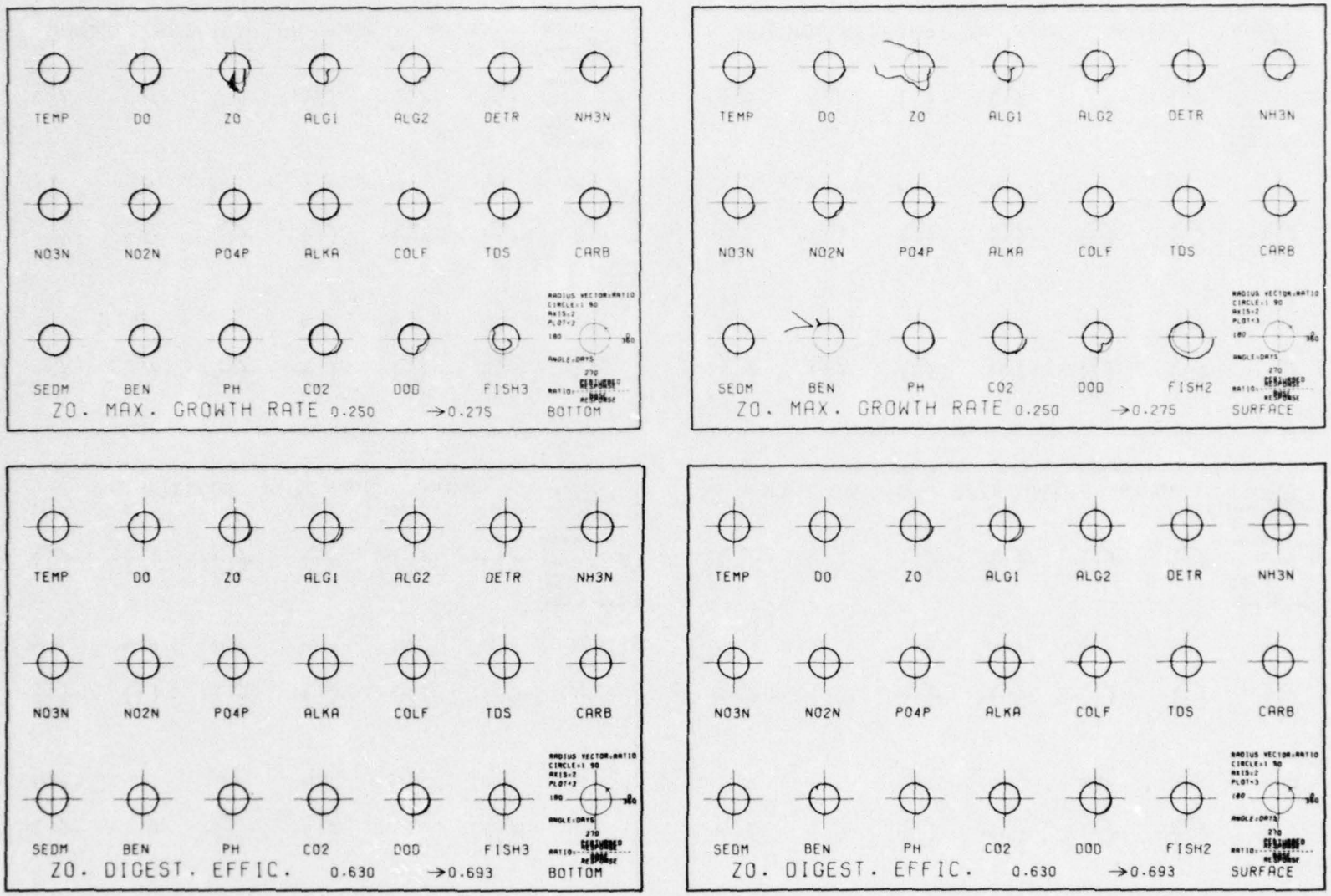


Figure 15. High nutrient case

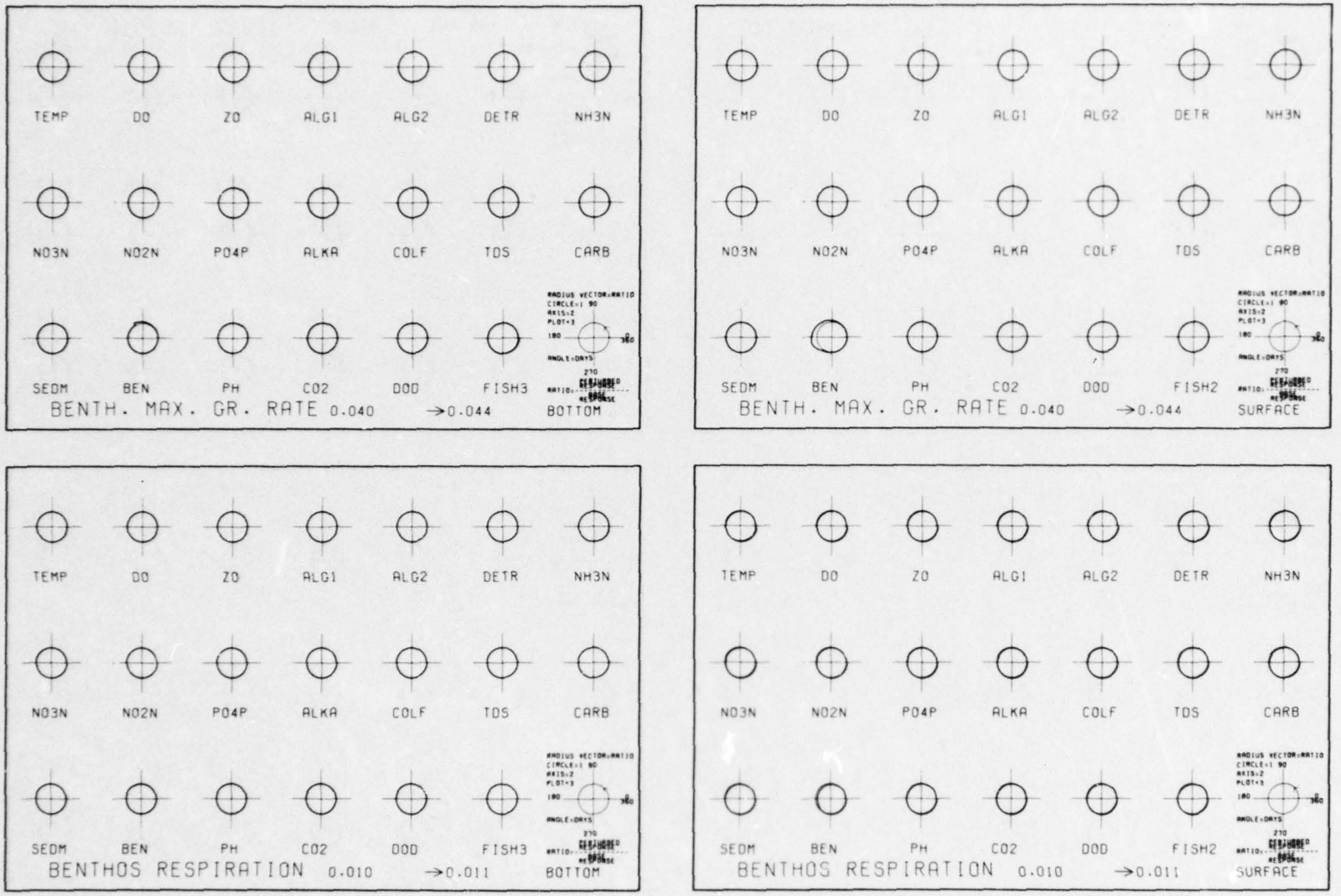
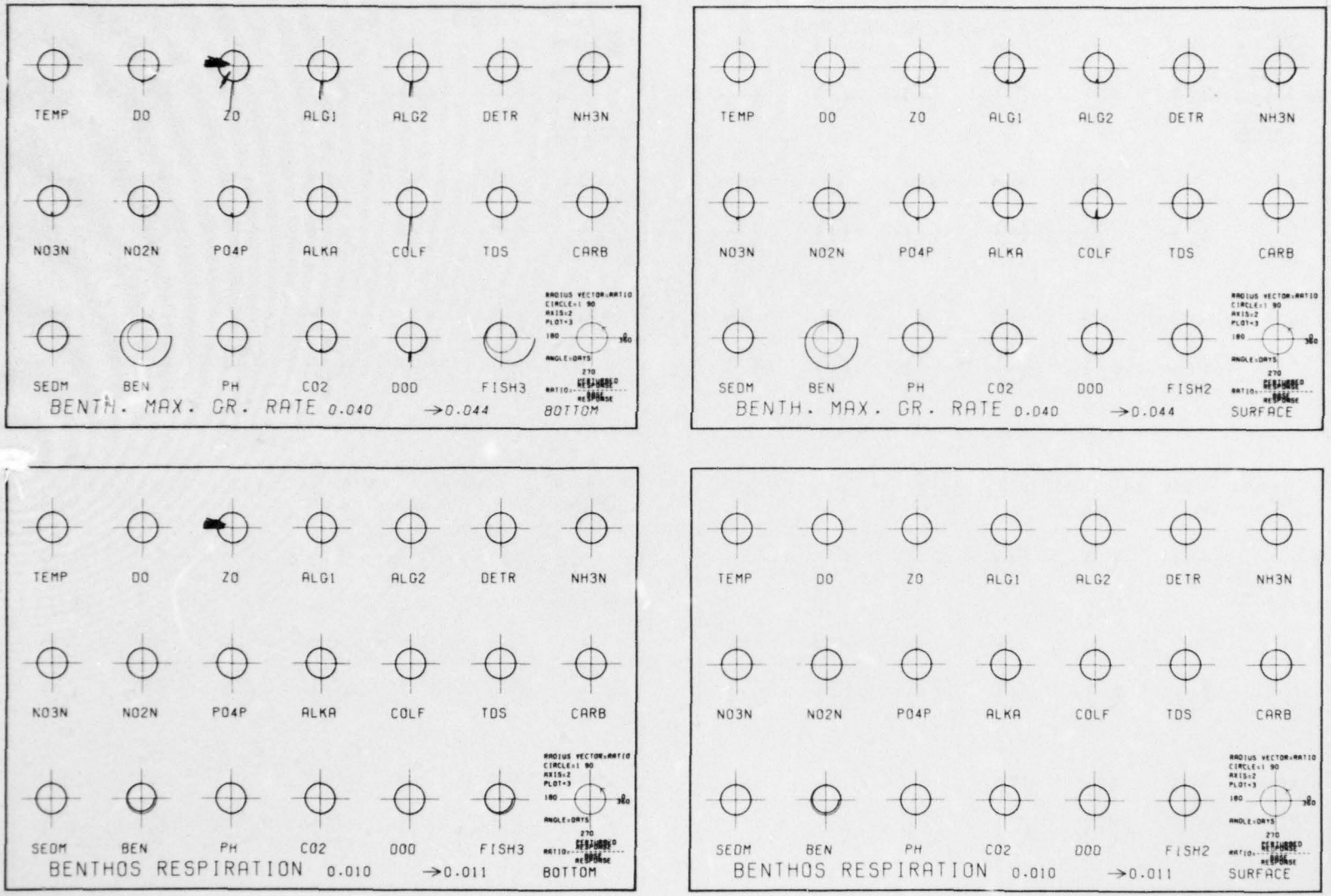


Figure 16. High nutrient case



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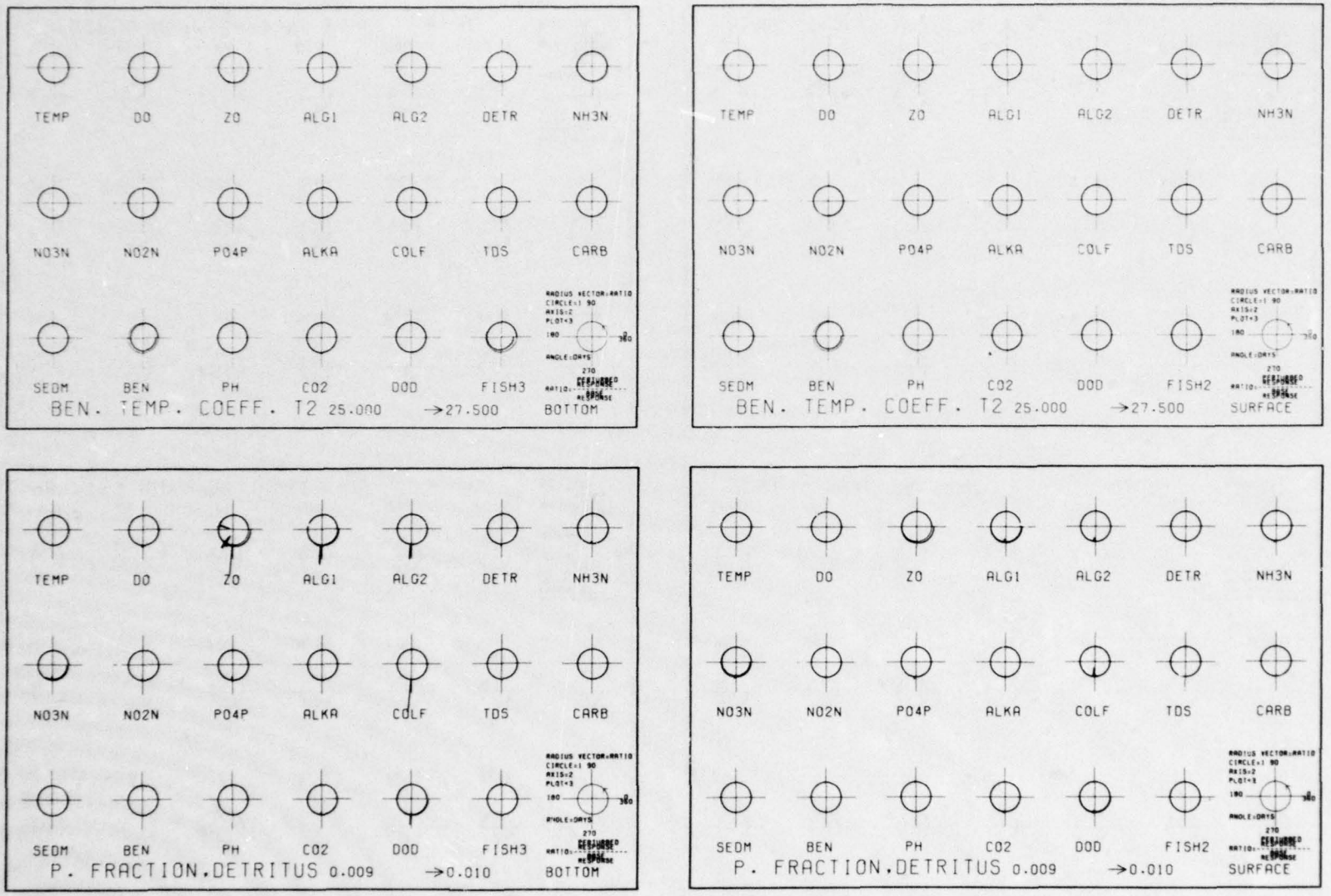
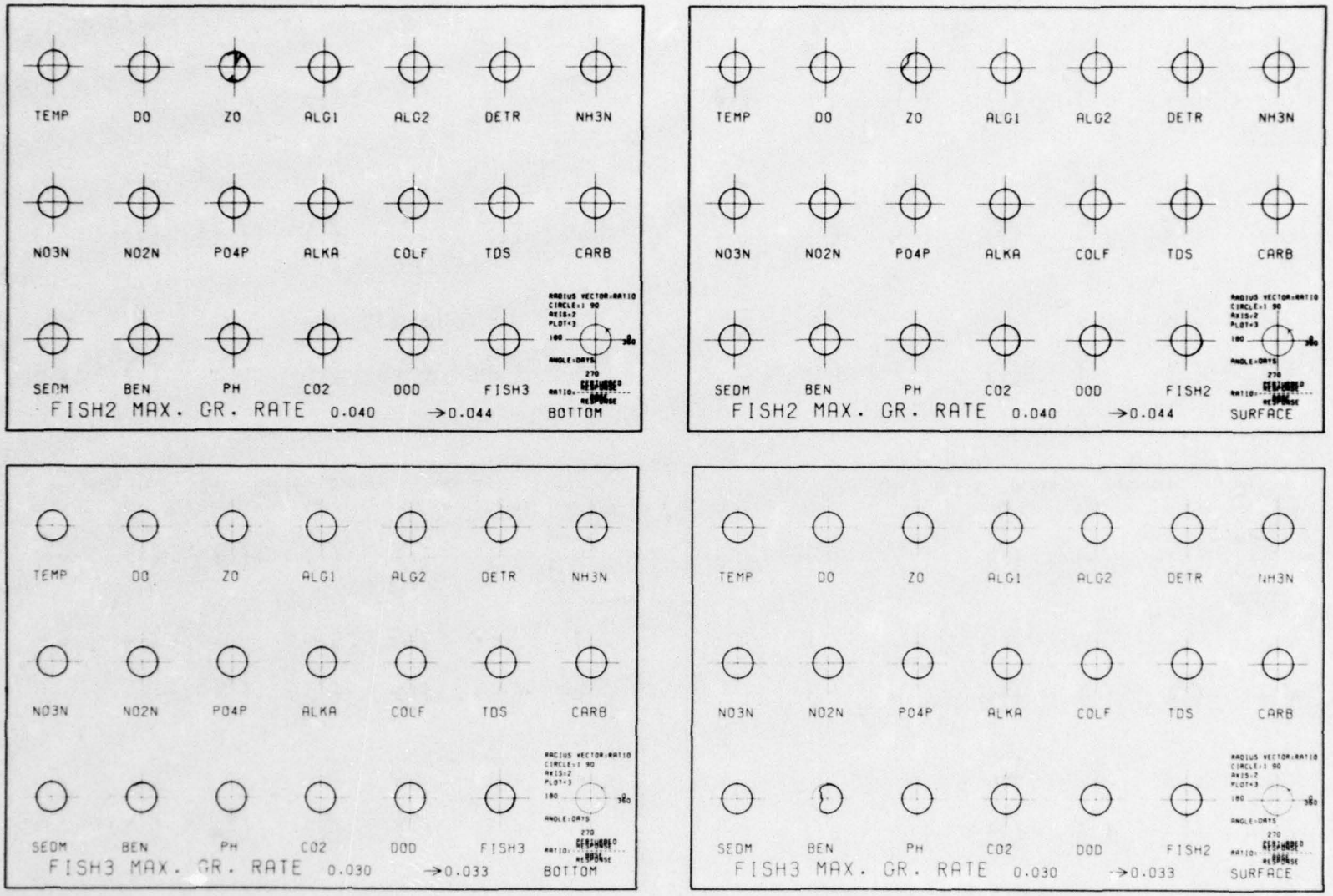


Figure 18. Low nutrient case



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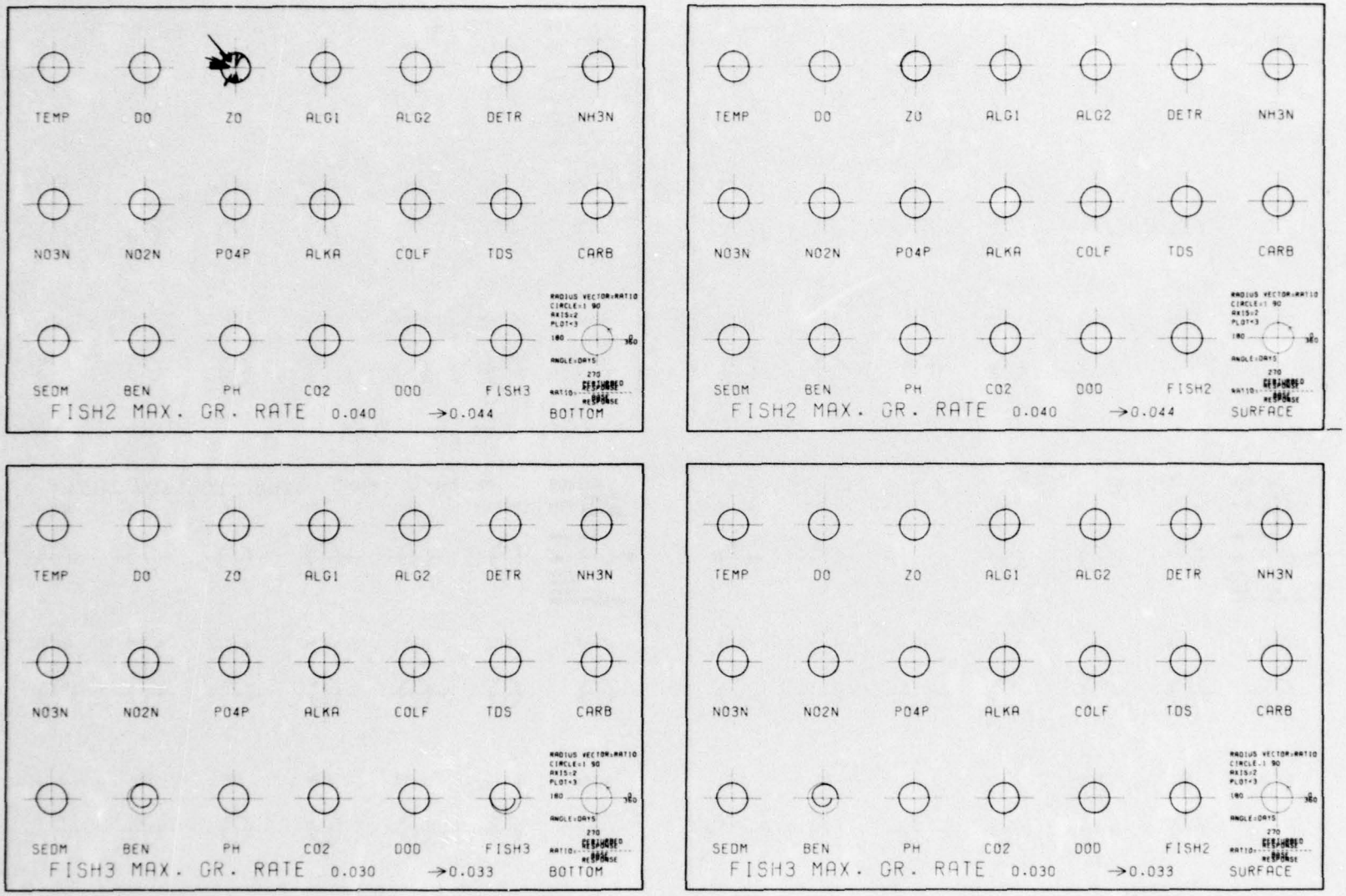
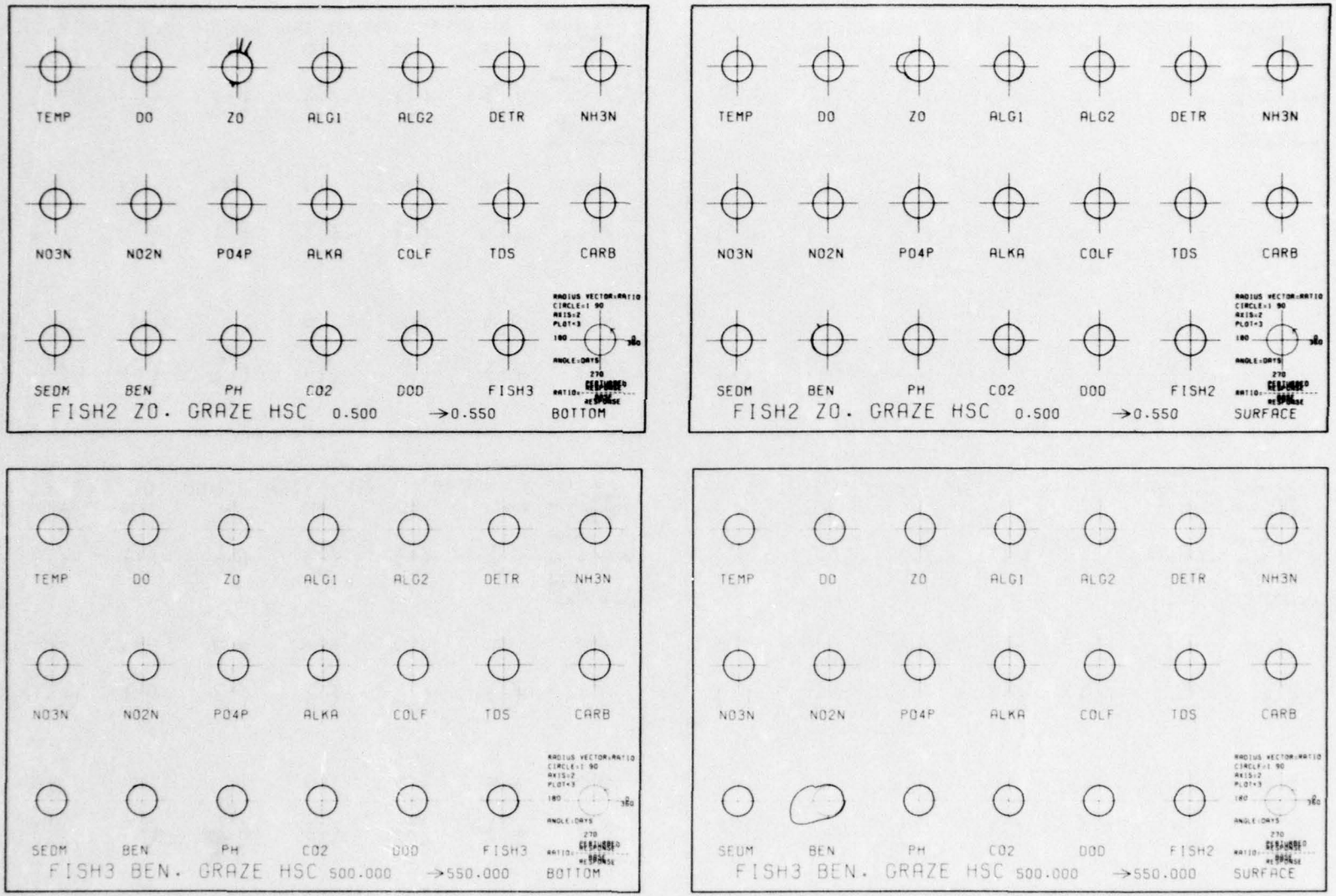


Figure 20. Low nutrient case



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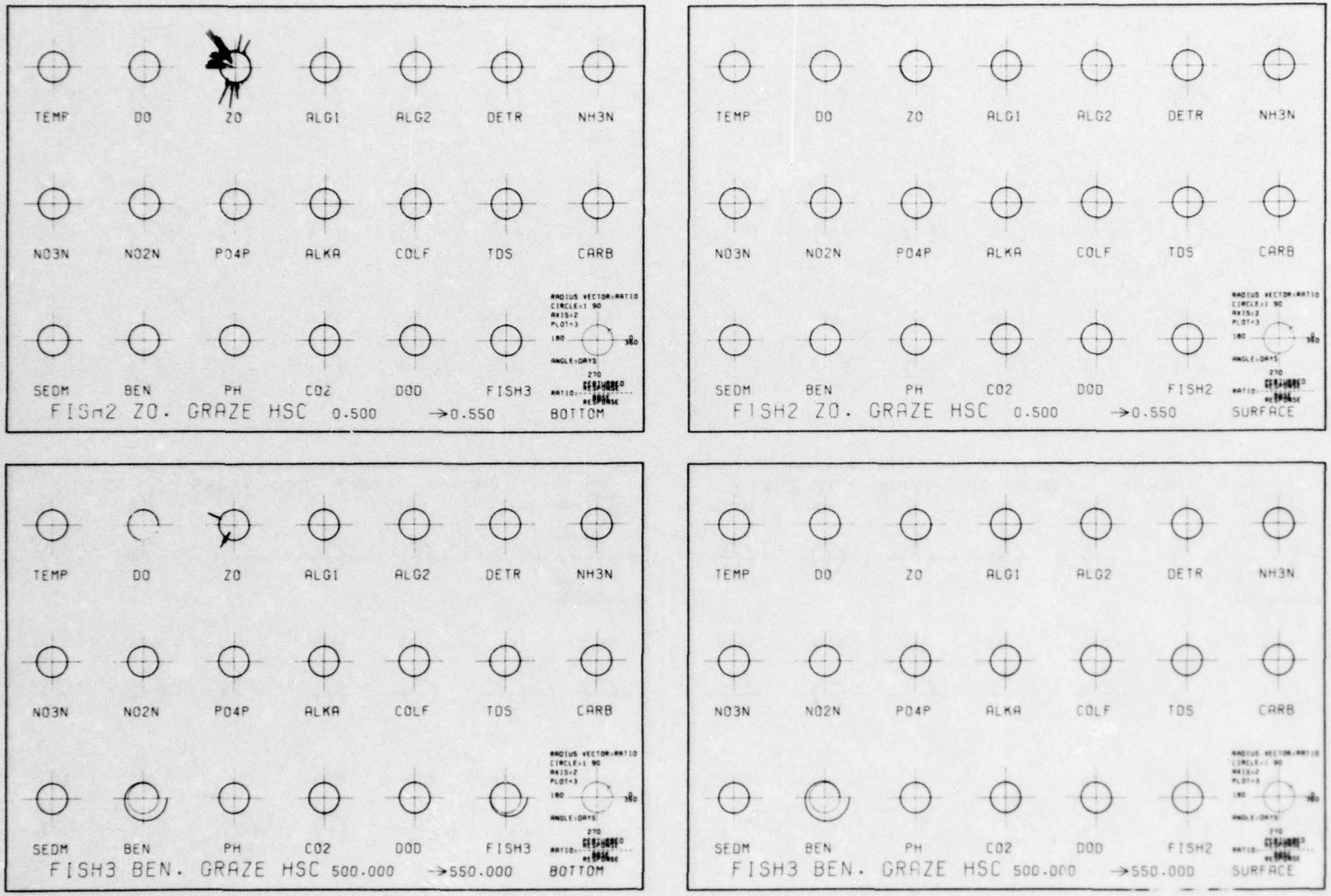

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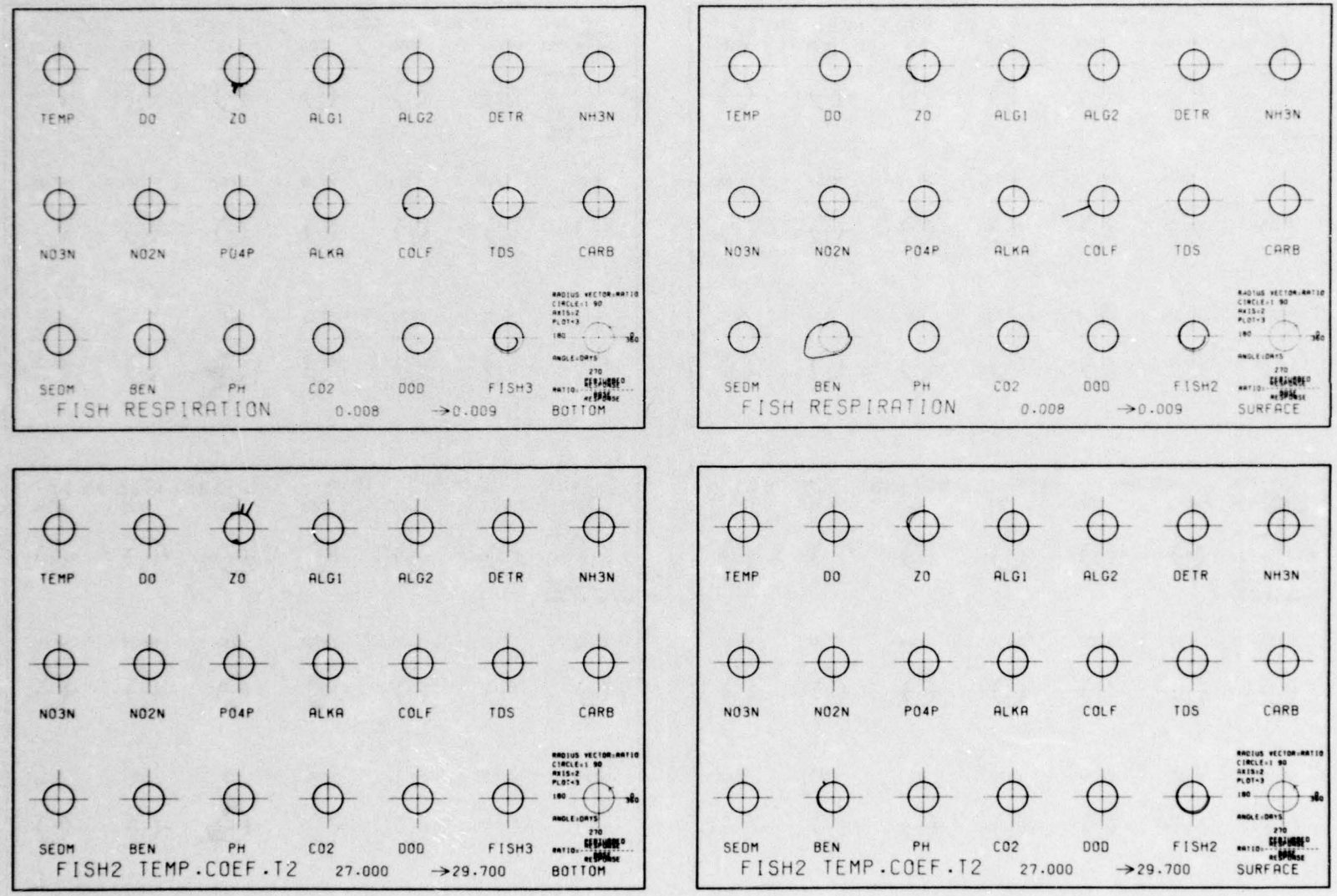

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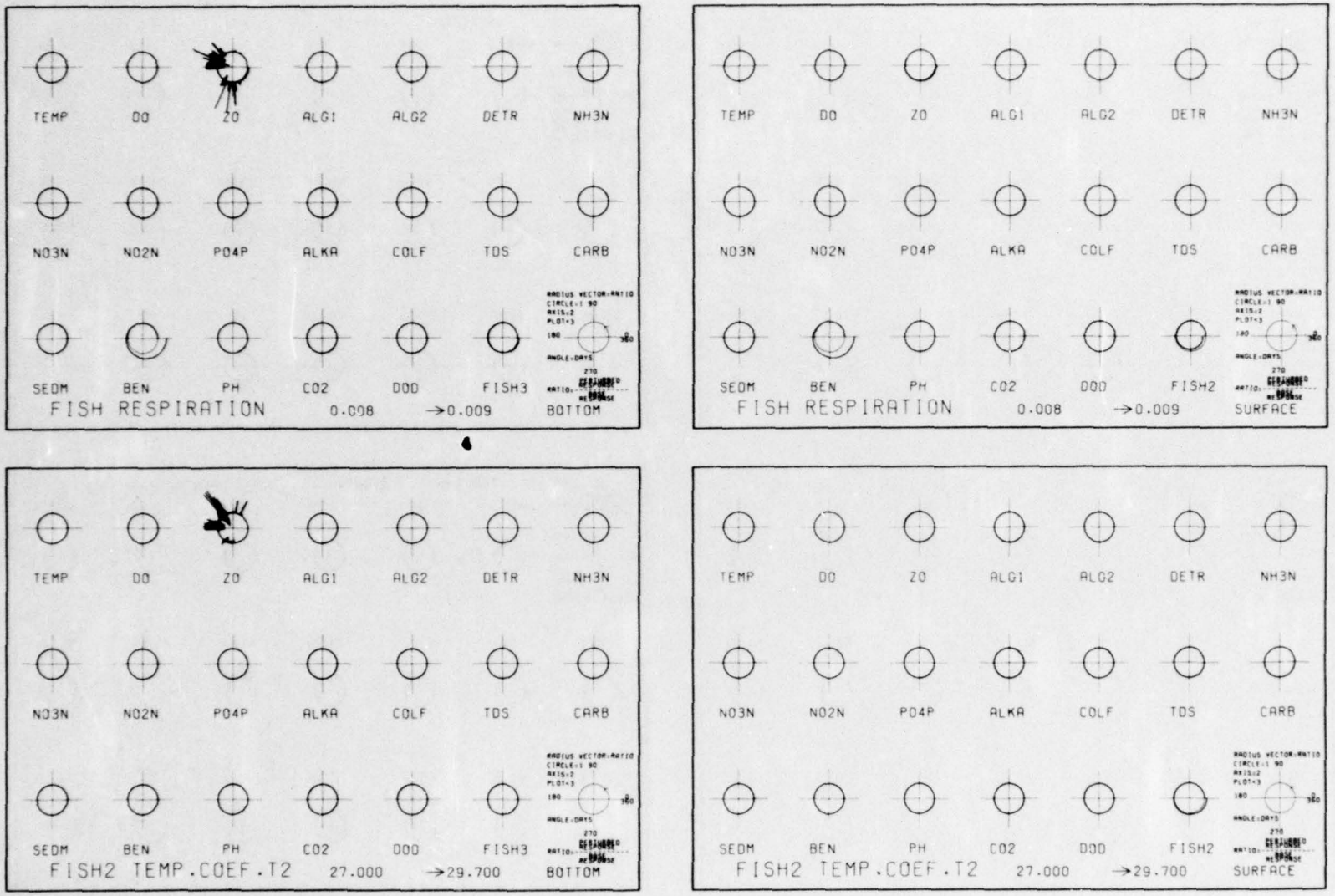

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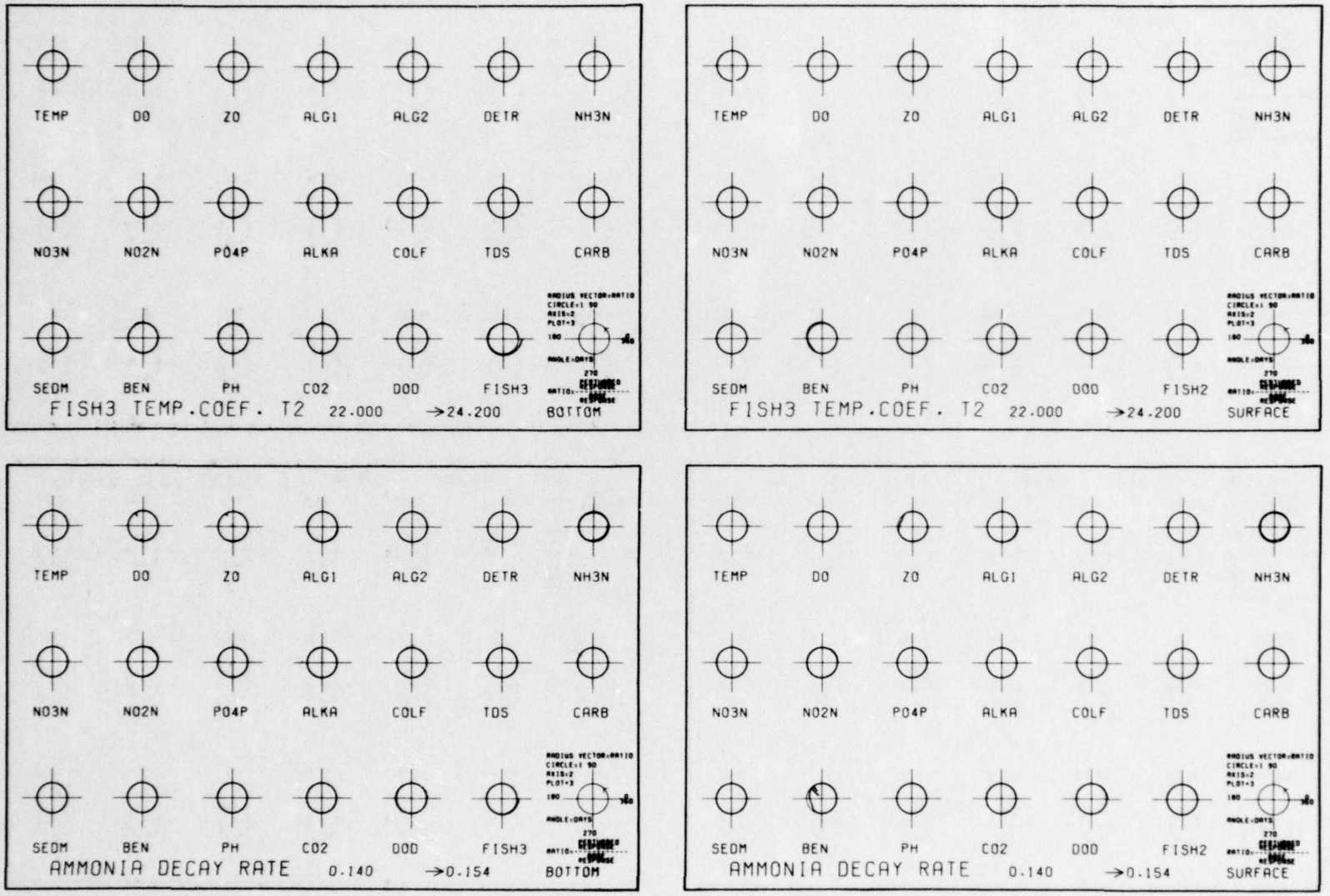

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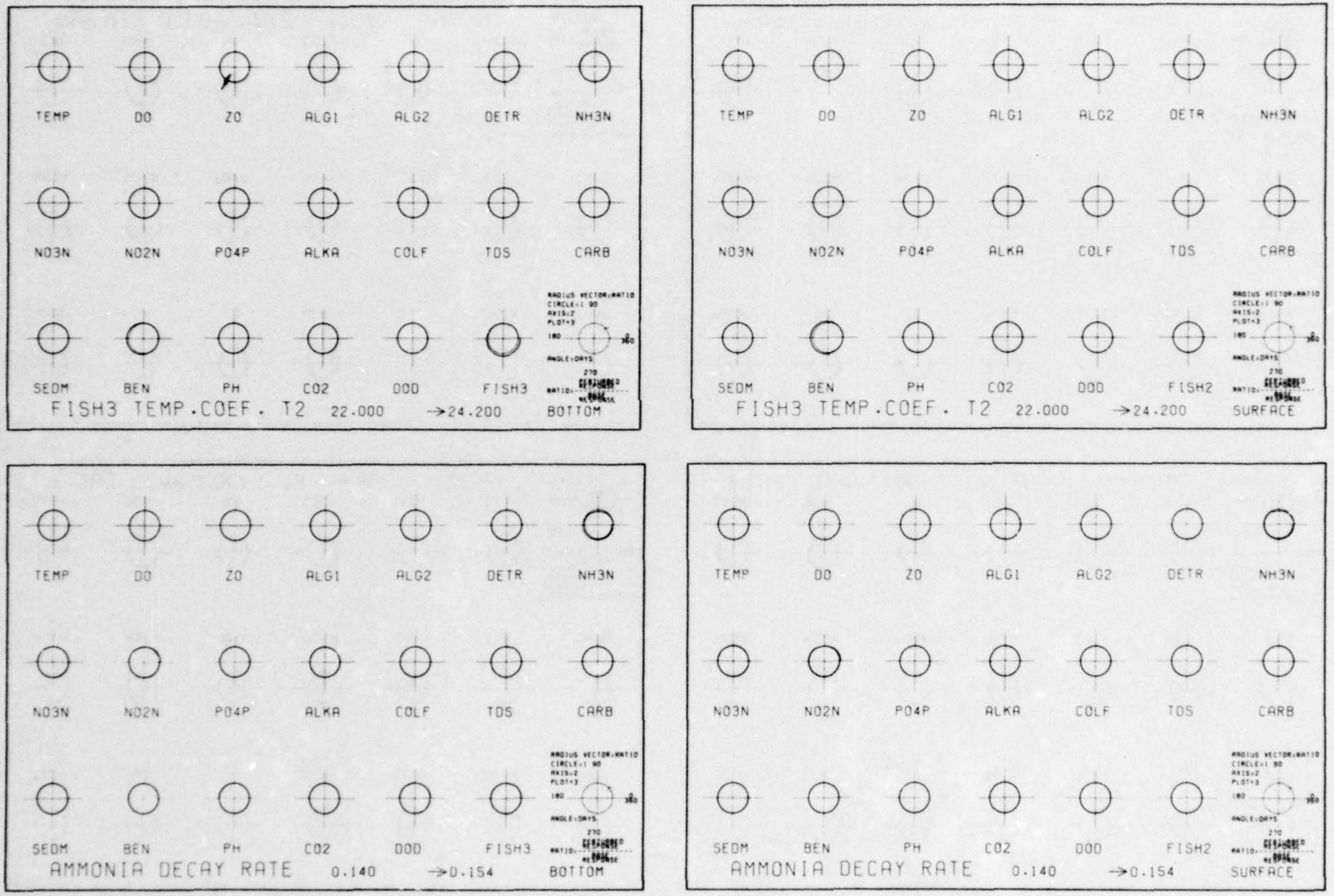


Figure 26. Low nutrient case

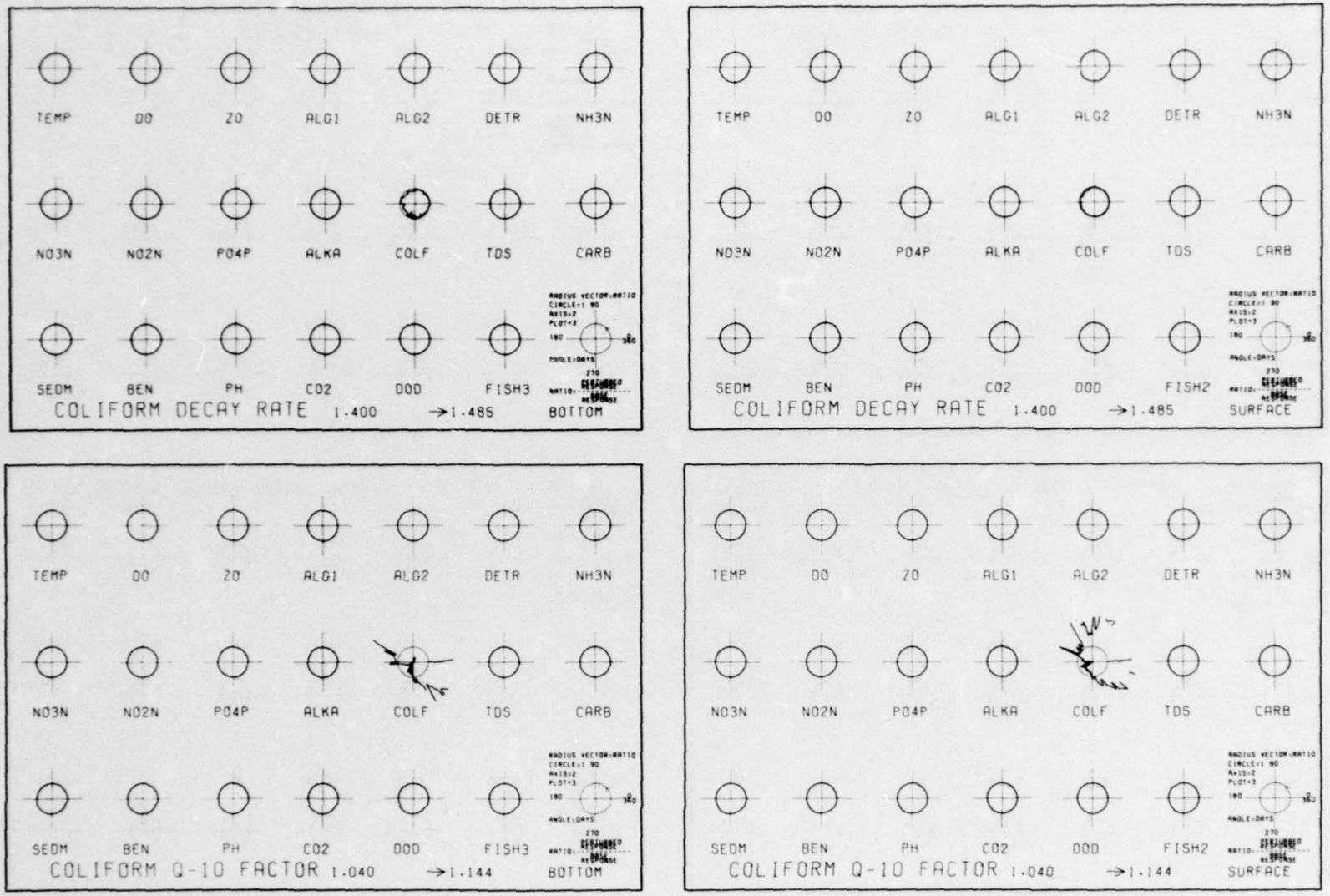
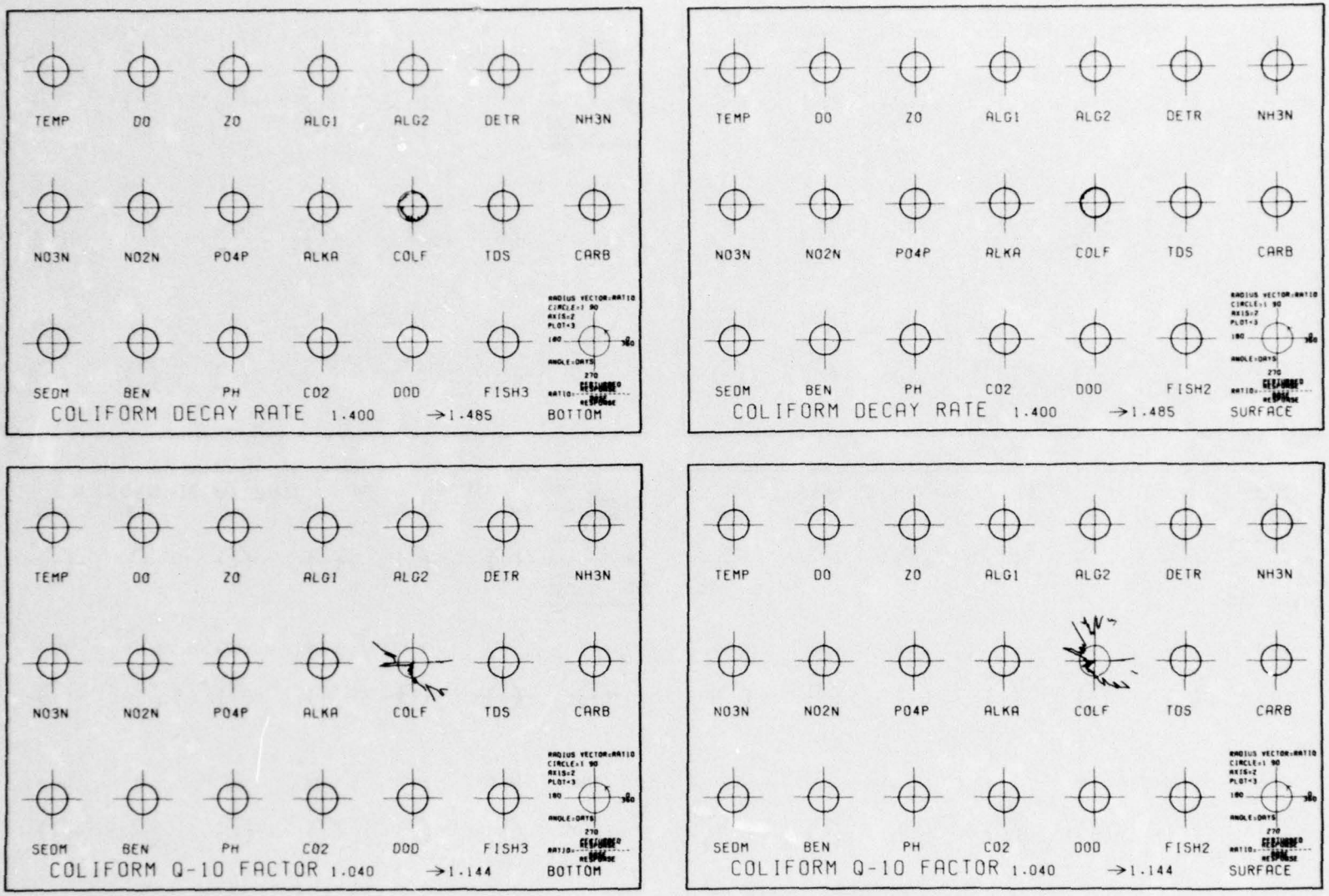


Figure 27. High nutrient case



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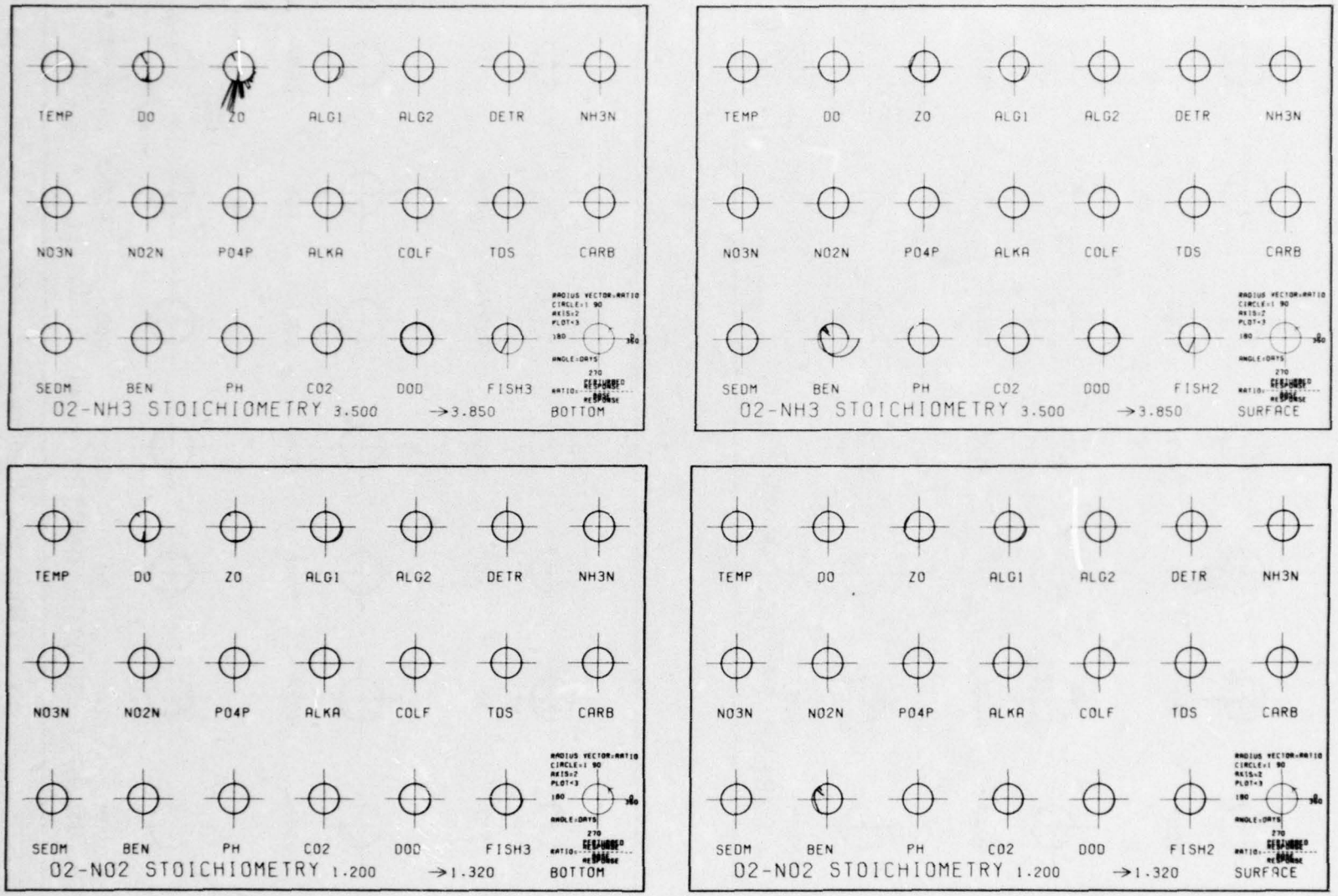
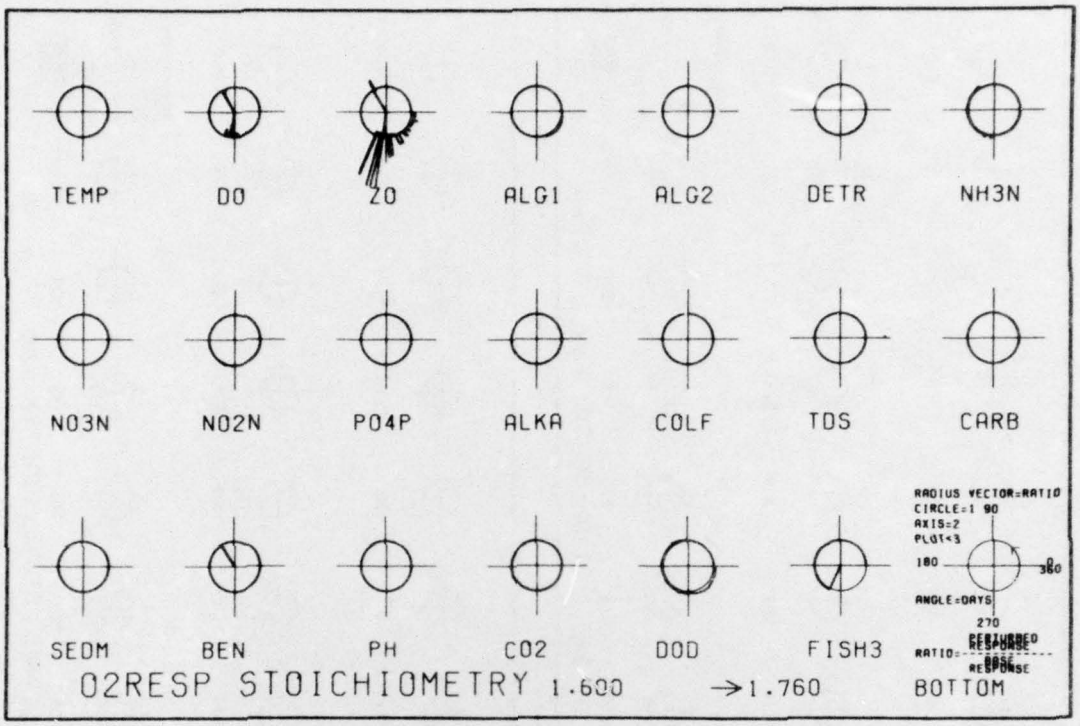


Figure 29. High nutrient case



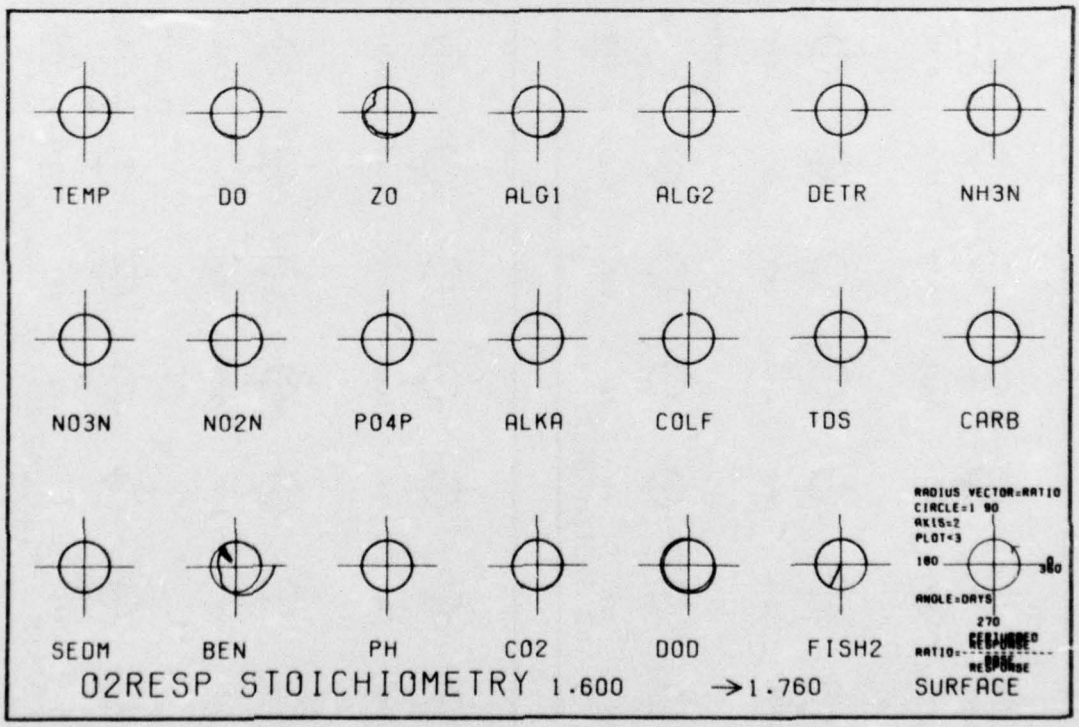


Figure 30. High nutrient case

In accordance with ER 70-2-3, paragraph 6c(1)(b), dated 15 February 1973, a facsimile catalog card in Library of Congress format is reproduced below.

Thornton, Kent W
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1 v. (various pagings) illus. 27 cm. (U. S. Waterways Experiment Station. Miscellaneous paper Y-76-4)
Prepared for Office, Chief of Engineers, U. S. Army, Washington, D. C.
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1. Computerized simulation. 2. Data collection. 3. Ecosystems. 4. Mathematical models. 5. Sensitivity. Water quality. I. Lessem, Allan S., joint author. II. U. S. Army. Corps of Engineers. (Series: U. S. Waterways Experiment Station, Vicksburg, Miss. Miscellaneous paper Y-76-4)
TA7.W34m no.Y-76-4